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HAÜY-BRAVAIS LATTICE AND OTHER CRYSTALLOGRAPHIC DATA FOR SODIUM MOLYBDO-TELLURATE*

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PART I. METHOD OF DETERMINING THE AXIAL ELEMENTS

INTRODUCTORY

The object of this section is to show the method used to choose the set of axial elements which is in best possible agreement with the law of Bravais.

The ideal set of axial elements should not only lead to simple indices for the known forms, for a number of different sets will fulfill this condition, but, as has been emphasized by Friedel[1] it should also give as much information as possible on the existing forms:

* Paper presented at the 13th annual meeting of the *Mineralogical Society of America*, Cambridge, Massachusetts, December 28, 1932.

[1] Leçons de Cristallographie professées à la Faculté des Sciences de Strasbourg, Georges Friedel, *Paris*, Berger-Levrault Ed., **1926**, p. 127.

it should enable the reader to infer the list of forms present on the crystals and the order of importance of these forms, from a mere inspection of the given axial elements.

That such an ideal set of axial elements does not exist, strictly speaking, is well known. The importance of a face is defined by its *frequency* of occurrence and its more or less perfect *development.* In terms of rate of growth, *slow faces* are the most important as they occur most frequently and usually are dominant faces. The forms of a crystalline species do not only depend on the space-lattice, but also on certain *disturbing factors*, such as on the length of time and other conditions of crystallization, presence of foreign ions in the solution, symmetry of the motif, etc. There is, nevertheless, a certain lattice, called the *Bravais lattice*[2] by G. Friedel, which approaches the ideal and will account for the observed facts better than any other. *Only in this Bravais lattice* is the importance of a face an increasing function of its reticular density. Moreover, the importance of a face does *not* usually increase with the reticular density in any other arbitrary lattice, however simple the symbols of the existing forms may be in that lattice.

It is chiefly because this fact has been overlooked that the parameters of crystalline species listed to date in standard reference books form such an incoherent chaos. The best remedy available to-day for all these inconsistencies is to adopt axial elements which express the Law of Bravais.

The determination of the axial elements will be explained here in detail for the sake of the *method* itself. The *results* will be summarized in Part II.

Measurements

The crystals belong to the pinacoidal class of the triclinic system. A total of fourteen forms were observed. Of these, ten were very good and four imperfect. The four imperfect forms being very rare, the existence of the center of symmetry cannot be questioned.

We observed the frequency of occurrence and the development of the forms on a number of crystals (over 20). We listed the forms in their order of decreasing importance, numbering them from 1 to

[2] We propose to call it *Haüy-Bravais lattice* instead, as it will be remembered that the term *Bravais lattices* has been used in English with a different meaning: the fourteen space-lattices that may be obtained by adding translations to the usual symmetry-operations (provided all these translations are greater than one-half the distance between the points of one of the seven primary lattices).

14. In the substance here studied, certain forms look equally important; we group them together, in parentheses, in the following manner:

(1, 2), (3, 4), (5, 6), (7, 8), 9, 10, 11, (12, 13, 14).

Besides the *five fundamental angles* necessary for our calculations, we measured several additional angles (eleven) against which the computed values were checked. The list of measured angles will be found in Table 1 (4th column). The faces are designated by their numbers in the 1st column; conventionally, 1′ will represent the face parallel to **1**, etc. An idea of the value of the series of measurements may be had from the 2nd and 3rd columns, giving respectively the number of measurements for each angle and the *probable error*. The value given under the heading "Measured" is in each case the *most probable value, i.e.* giving the *least mean quadratic error.*

The measurements were made with the non-modified type of a Wollaston reflection goniometer.

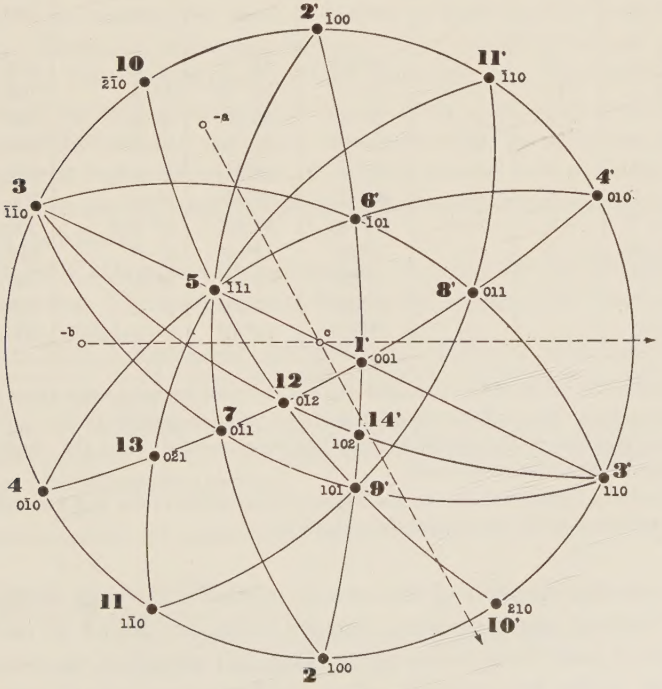


FIG. 1. Projection (I).

Calculation of the 1st Set of Axial Elements

A projection of the crystal is made by using a Wulff stereographic net (Fig. 1). A preliminary set of axial elements is determined by assigning simple Miller symbols to the most common and best developed faces: **1**′(*001*), **2**(*100*), **4**′(*010*), **3**′(*110*), and **6**′($\bar{1}01$). In this calculation, we use as fundamental data five interfacial angles chosen from those giving the best measurements.

Table 1

Comparison between Measured and Computed Angles

Angle: (face numbers)	Number of readings	Probable error	Measured	Computed	Angle: (face symbols)	
					Lévy	Miller
2 ∧ 4	23	8.9′	62°56′	—	$g^1 \cdot e^1$	010∧01$\bar{1}$
1 ∧ 4	17	8.2′	79°58′	—	$h^1 \cdot e^1$	$\bar{1}$00∧01$\bar{1}$
2′∧ 3	12	8.2′	63°40′	—	$g^1 \cdot p$	0$\bar{1}$0∧00$\bar{1}$
1′∧ 2	18	9.9′	82°42′	—	$h^1 \cdot g^1$	100∧010
1 ∧ 6	13	12.1′	49°17′	—	$h^1 \cdot m$	$\bar{1}$00∧$\bar{1}$10
2 ∧ 6	13	9.1′	47°52′	48° 1′	$g^1 \cdot m$	010∧$\bar{1}$10
1 ∧ 3	11	9.6′	73° 1′	73° 9′	$h^1 \cdot p$	$\bar{1}$00∧00$\bar{1}$
1′∧ 5	10	13.3′	58°19′	58°10′	$h^1 \cdot a^1$	100∧10$\bar{1}$
1 ∧ 8	10	16.5′	43° 8′	43° 5′	$h^1 \cdot d^{1/2}$	$\bar{1}$00∧$\bar{1}$1$\bar{1}$
2 ∧11	6	16.1′	33°26′	33°24′	$g^1 \cdot e^{1/2}$	010∧02$\bar{1}$
1 ∧ 9	5	—	41°47′	41°50′	$h^1 \cdot t$	$\bar{1}$00∧$\bar{1}\bar{1}$0
1′∧ 7	5	—	54°18′	54°26′	$h^1 \cdot b^{1/2}$	100∧11$\bar{1}$
2′∧10	3	—	33°22′	33°40′	$g^1 \cdot i^1$	0$\bar{1}$0∧0$\bar{1}\bar{1}$
1 ∧14	2	—	25°29′	25°24′	$h^1 \cdot h^3$	$\bar{1}$00∧$\bar{2}$10
1′∧12	2	—	31°38′	31°53′	$h^1 \cdot {}_3a$	100∧21$\bar{1}$
1′∧13	1	—	75°33′	74°56′	$h^1 \cdot b^1 d^{1/3} g^{1/2}$	100∧12$\bar{2}$

N.B.—The value of the *measured angle* is the *most probable value* given to the closest minute. The *probable error* is based on a value computed to the tenth of a minute; mention of the probable error has been omitted when the number of readings in the series is too small.

The Lévy form-symbols and the Miller face-symbols in the last two columns are in reference to the set of axial elements (VI).

A peculiar property of the crystals studied is the large number of well defined zones present: thirteen zones are found in each of which at least three forms occur. This fact simplifies the determination of the face symbols, *all of which* can be obtained from the

given five by applying only the "Addition and Subtraction Rule."[3] This can easily be seen from Fig. 1; the nine unknown symbols are found in the following order: **8′, 5, 7, 9′, 10′, 12, 14′, 11, 13.**

Simple trigonometric calculations lead to the axial elements:[4]

$$\breve{a}:\breve{b}:\breve{c}=1.1082:1:1.0219,$$

$$\alpha=105°14', \qquad \beta=103°37', \qquad \gamma=60°45', \qquad \text{(I)}$$

$$A=79°58', \qquad B=82°42', \qquad C=117°4'.$$

The eleven angles which have been measured in addition to the five fundamental ones, are now computed from the latter. Their measured and computed values may be compared in Table 1.

Improvement in the Preliminary Set of Axial Elements

When very many measurements are available, it is possible to find as many different unit-cells (or sets of axial elements) as there are ways of choosing five angles out of the number that are available. Provided all the measurements are about equally good, it is possible to combine them all in such a way as to obtain a *mean unit-cell* which is probably closer to the truth than any of the above. The method has been discussed by Mallard.[5] It leads to as many differential equations between the parameters of the polar lattice as there are superabundant measurements; the method of the least squares reduces them to five linear equations containing the corrections (to be applied to the parameters) as variables; these corrections being determined, it is easy to find the corrections to be made to the unit-cell. Friedel gives a somewhat modified method in his text-book.

We have attempted unsuccessfully to apply the method in the present case. The reason for its failure is that the preliminary unit-

[3] Dr. Austin F. Rogers called attention to the value of this simple rule at the 1924 meeting of the *Mineralogical Society of America*, at Ithaca, N. Y., *Am. Min.*, **10,** 68, 1925; **11,** 303, 1926.

It may be interesting to know, in this connection, how the French crystallographer expresses this rule: "The plane *tangent to the edge* of two given faces (*hkl*) and (*pqr*) has the following indices:

$$h+p, \qquad k+q, \qquad l+r.$$

The plane *tangent to the supplementary edge* has the indices:

$$h-p, \qquad k-q \qquad l-r."$$

(See Friedel, *op. cit.*, p. 229).

[4] We use the abbreviated notation:

$$A=(010\wedge001), \quad B=(001\wedge100), \quad C=(100\wedge010),$$

for the sides of the spherical triangle 100.010.001.

[5] Traité de Cristallographie, Ernest Mallard, Tome I, p. 295, **1879.**

cell (I) had been determined from five measurements which were decidedly better than the others.

Law of Haüy

Our unit-cell (I) satisfies the Law of Haüy, in its vaguest form, that is to say, that the face indices referred to this lattice are small integers.

Many other unit-cells can be found which fulfill the same condition. For instance, if we start from the same fundamental angles and the following symbols: **1**′(001), **2**(100), **4**′($\bar{1}$10), **3**′(110), and **6**′($\bar{1}$01), we arrive at these results: $\breve{a}:\breve{b}:\breve{c}:=0.9691:1:1.0196$,

$$\alpha=105°14', \qquad \beta=97°26', \qquad \gamma=88°29', \qquad \text{(II)}$$
$$A=74°50', \qquad B=82°42', \qquad C=90°28'.$$

This second unit-cell leads to simple indices; the indices are even simpler with cell (III), in which $\dot{c}=0.5098$, all the other axial elements remaining as in (II). Cell (III) is found by starting from the same five fundamental angles and the symbols: **1**′(001), **2**(100), **4**′($\bar{1}$10), **3**′(110), and **6**′($\bar{2}$01).

If $(h'k'l')$ is the symbol of a face referred to lattice (I), let $(h''k''l'')$ and $(h'''k'''l''')$ represent the same face referred to latices (II) and (III), respectively. The transformation formulae are:

$$h''=2h'-k', \qquad k''=k', \qquad l''=2l',$$

and

$$h'''=2h'-k', \qquad k'''=k', \qquad l'''=l'.$$

How are we to choose from all the possibilities?

Law of Bravais

The answer to this question is: By applying the Law of Bravais.

We compute the reticular densities of the forms in the different cases, *i.e.* referred to the various lattices, and see in which one the list of forms arranged according to decreasing reticular densities is in best agreement with the *observed* order of importance.

The formula giving the area $S(hkl)$ of the elementary parallelogram (mesh or plane unit-cell) in the reticular plane (hkl) is known and may be written as follows for the triclinic system:

$$S^2(hkl)=h^2S^2(100)+k^2S^2(010)+l^2S^2(001)$$
$$+2[hkS(100)S(010)\cos C+klS(010)S(001)\cos A+lhS(001)S(100)\cos B],$$

in which

$$S(100)=bc\sin\alpha,$$
$$S(010)=ca\sin\beta,$$
$$S(001)=ab\sin\gamma.$$

Following Friedel, we compute the value S^2 instead of the reticular density, the latter being of course inversely proportional to S. The list of the first two hundred reticular planes is given in Table 2 in the order of decreasing densities for the first lattice (unit-cell I). Known forms, *i.e.* forms which occur on the crystals, are italicized.

TABLE 2

PLANES OF LATTICE (I) LISTED IN ORDER OF DECREASING RETICULAR DENSITIES OR INCREASING S^2.

No.	(I)	S^2	(I)	S^2	(I)	S^2	(I)	S^2
1	*001*	0.94	201	5.31	230	8.87	231	11.40
2	*100*	0.97	$12\bar{2}$	5.62	130	8.91	113	11.45
3	*110*	1.20	012	5.69	$30\bar{1}$	8.96	$32\bar{3}$	11.68
4	*010*	1.21	121	5.76	$21\bar{3}$	8.97	$42\bar{1}$	11.72
5	*$\bar{1}11$*	1.52	112	6.16	311	9.03	$\bar{1}13$	11.97
6	*$\bar{1}01$*	1.66	021	6.52	$\bar{1}21$	9.23	$31\bar{3}$	12.12
7	*$0\bar{1}1$*	1.78	$1\bar{1}2$	6.66	$12\bar{3}$	9.31	$43\bar{1}$	12.25
9	*101*	2.15	$31\bar{1}$	6.84	$23\bar{2}$	9.41	$41\bar{1}$	12.41
8	*011*	2.52	221	6.95	$22\bar{3}$	9.52	$03\bar{2}$	12.42
	111	2.74	310	7.00	122	9.55	$23\bar{3}$	12.49
10	*210*	3.12	$2\bar{1}0$	7.08	$33\bar{1}$	9.86	$\bar{1}22$	12.53
11	*$1\bar{1}0$*	3.17	$32\bar{1}$	7.14	$13\bar{2}$	9.94	410	12.82
	$21\bar{1}$	3.20	$\bar{1}12$	7.17	321	10.07	$3\bar{1}0$	12.92
	$11\bar{2}$	3.71	320	7.67	103	10.11	312	12.93
	$12\bar{1}$	3.79	$11\bar{3}$	7.77	301	10.41	031	12.95
	120	3.84	$\bar{1}20$	7.79	$1\bar{2}2$	10.54	$13\bar{3}$	13.26
	$1\bar{1}1$	3.98	$\bar{2}11$	7.90	$\bar{2}12$	10.59	$2\bar{2}1$	13.36
12	*$0\bar{1}2$*	4.21	$2\bar{1}1$	8.12	$03\bar{1}$	10.73	$\bar{3}11$	13.50
	$\bar{1}02$	4.23	$23\bar{1}$	8.20	013	10.74	331	13.54
	$\bar{1}11$	4.24	$1\bar{2}1$	8.23	$33\bar{2}$	10.83	$11\bar{4}$	13.70
	$20\bar{1}$	4.34	$12\bar{2}$	8.47	$\bar{2}03$	10.85	203	13.76
	$22\bar{1}$	4.49	$33\bar{1}$	8.49	$30\bar{2}$	11.04	$41\bar{2}$	13.88
	211	4.91	$0\bar{1}3$	8.51	$0\bar{2}3$	11.04	$\bar{2}21$	13.88
13	*$0\bar{2}1$*	5.04	$31\bar{2}$	8.54	$2\bar{1}2$	11.04	302	13.94
	$21\bar{2}$	5.15	212	8.58	$1\bar{1}3$	11.20	213	14.11
14	*102*	5.20	$\bar{1}03$	8.66	131	11.20	$43\bar{2}$	14.18
	$3\bar{1}1$	14.22	$14\bar{1}$	16.60	114	18.61	$\bar{2}30$	20.72
	$24\bar{1}$	14.34	$\bar{1}31$	16.64	$\bar{1}14$	18.65	$1\bar{2}4$	20.76
	322	14.35	$14\bar{2}$	16.69	313	18.71	$\bar{3}04$	20.80
	430	14.61	$32\bar{4}$	16.76	$04\bar{1}$	18.84	$2\bar{3}1$	21.03
	$21\bar{4}$	14.66	$43\bar{3}$	16.78	$53\bar{1}$	19.00	$\bar{4}11$	21.05
	$0\bar{1}4$	14.69	$13\bar{2}$	16.84	141	19.07	$40\bar{3}$	21.06
	$1\bar{2}3$	14.71	032	16.87	$52\bar{2}$	19.11	$43\bar{4}$	21.24
	$\bar{1}30$	14.84	223	16.88	412	19.24	133	21.39

TABLE 2 (*Continued*)

No.	(I)	S^2	(I)	S^2	(I)	S^2	(I)	S^2
	$12\bar{4}$	14.87	104	16.90	520	19.27	$0\bar{3}4$	21.41
	$1\bar{3}1$	14.90	$41\bar{3}$	17.21	$34\bar{1}$	19.43	214	21.51
	$\bar{1}04$	14.96	$3\bar{1}2$	17.38	$53\bar{2}$	19.49	$\bar{2}14$	21.58
	$34\bar{1}$	15.01	$23\bar{4}$	17.44	$3\bar{2}0$	19.52	041	21.80
	411	15.09	401	17.46	$14\bar{3}$	19.64	$52\bar{3}$	21.83
	421	15.14	$31\bar{4}$	17.57	$51\bar{1}$	19.93	$53\bar{3}$	21.84
	$\bar{2}13$	15.15	$1\bar{1}4$	17.62	$34\bar{2}$	20.07	$\bar{2}23$	21.87
	123	15.21	$44\bar{1}$	17.62	$44\bar{3}$	20.19	225	22.03
	132	15.36	431	17.62	$\bar{3}13$	20.27	233	22.07
	023	15.49	014	17.66	$\bar{1}32$	20.32	$51\bar{2}$	22.14
	$40\bar{1}$	15.52	$\bar{1}23$	17.71	$2\bar{2}3$	20.33	521	22.16
	$42\bar{3}$	15.78	$34\bar{3}$	18.07	530	20.39	$54\bar{1}$	22.18
	232	15.80	332	18.18	$32\bar{1}$	20.44	215	22.22
	$2\bar{1}3$	15.83	$52\bar{1}$	18.26	$\bar{3}21$	20.47	$4\bar{1}1$	22.25
	$\bar{3}12$	15.95	241	18.27	323	20.49	$\bar{2}31$	22.28
	340	16.28	$33\bar{4}$	18.37	510	20.58		
	140	16.41	$13\bar{4}$	18.45	$4\bar{1}0$	20.72		

N.B.—Symbols of known forms are italicized.

It is easy to see how well this list agrees with the observed facts (relative importance of the faces); there is only one exception: the order of faces **8** and **9** is reversed. The first nine forms in the list of decreasing reticular densities are all present. The tenth is unknown but the next two are present again. The other gaps are larger. The influence of disturbing factors, although very little known, probably becomes more important as we go down the list and may account for the vacant spaces. The importance of the last three forms, it must be admitted, is very small; they represent minor truncations, each of them has only been found once on the crystals examined.

The values of S^2 also show why faces **3** and **4**, **1** and **2**, and (less plainly, it is true) **5** and **6** are about equally important.

We have computed the values of S^2 for many more forms than were necessary to check the agreement with the Law of Bravais. We have done this in order to show what small importance must be attached to the expression "simplicity of indices." It is instructive to read the list in that respect. Symbols containing 1, 2, and 3 as indices, for instance, range from $S^2=7.14$ (for $32\bar{1}$, 38th form) to $S^2=22.28$ (for $\bar{2}31$, 202nd form). Faces with "simple" indices

follow faces with higher indices, in a great many cases. No apparent law is to be inferred from the "simplicity" of the indices.

That the "simplicity" of the indices is not a sufficient reason to account for the presence or absence of a face, is shown even better by Table 3 where a series of forms with equally simple indices are

TABLE 3

LIST OF FORMS WITH EQUALLY SIMPLE INDICES REFERRED TO LATTICE (I)

Forms:	*001*	*100*	*010*									
S^2:	0.94	0.97	1.21									
	110	*$\bar{1}$01*	*0$\bar{1}$1*	*101*	*011*	*1$\bar{1}$0*						
	1.20	1.66	1.78	2.15	2.52	3.17						
	$\bar{1}\bar{1}$1	111	1$\bar{1}$1	$\bar{1}$11								
	1.52	2.74	3.98	4.24								
	210	120	*0$\bar{1}$2*	$\bar{1}$02	20$\bar{1}$	*02$\bar{1}$*	*102*	201	012	021	2$\bar{1}$0	$\bar{1}$20
	3.12	3.84	4.21	4.23	4.34	5.04	5.20	5.31	5.69	6.52	7.08	7.79

N.B.—Known forms are italicized.

listed in the order of decreasing reticular densities. All the forms of the same series (same horizontal line), having similar indices, ought to have an equal opportunity to be present if the "simplicity of indices" were a sufficient criterion. We see, on the contrary, that all important known forms generally appear at the beginning of each series. The exception of the last three underlined forms has little weight in this discussion, for the reasons stated above. It is however significant that, although disturbing influences were unquestionably present, they cannot entirely counteract the dominant influence of the lattice, since the three forms that are exceptions still occur among the first seven of the twelve in the series.

Similar lists can be made for the second and third lattices (unit cells II and III). It immediately becomes obvious that these lattices do not express the facts observed with respect to the relative importance of existing forms. To give complete lists, such as that of Table 2, would increase the size of this paper beyond reasonable bounds. The important point is to know where the existing forms fall in the lists. We arranged the fourteen known forms in the order of decreasing reticular densities and for each one indicated the rank

TABLE 4

RANK OCCUPIED BY THE KNOWN FORMS IN THE LISTS OF FORMS ARRANGED ACCORDING TO DECREASING RETICULAR DENSITIES FOR LATTICES (I), (II), (III), (IV), (V) AND (VI)

I				II				III				IV				V	VI
No.	Symbol	S^2	Rank	No.	Symbol	S^2	Rank	No.	Symbol	S^2	Rank	No.	Symbol	S^2	Rank	Symbol	Symbol
1	001	0.94	1	1	001	0.94	1	1	001	0.94	1	6	100	0.55	1	010	100
2	100	0.97	2	2	100	3.87	4	2	100	0.97	3	9	010	0.71	2	100	010
3	110	1.20	3	6	$\bar{1}01$	4.33	5	3	110	1.91	6	1	$1\bar{1}0$	1.25	3	001	001
4	010	1.21	4	9	101	5.29	6	4	$1\bar{1}0$	1.94	7	2	110	1.28	4	$\bar{1}01$	$0\bar{1}1$
5	$\bar{1}11$	1.52	5	3	110	7.65	11	5	$\bar{1}11$	2.11	8	4	001	1.60	6	$0\bar{1}1$	$\bar{1}01$
6	$\bar{1}01$	1.66	6	4	$1\bar{1}0$	7.77	12	14	101	2.15	9	3	$\bar{1}\bar{1}1$	1.61	7	$1\bar{1}0$	$1\bar{1}0$
7	$0\bar{1}1$	1.78	7	13	$1\bar{1}1$	8.20	13	7	$1\bar{1}1$	2.63	11	5	$20\bar{1}$	2.12	9	$\bar{1}11$	$\bar{1}11$
9	101	2.15	8	5	$\bar{1}\bar{1}2$	8.45	14	8	$\bar{1}11$	3.14	12	7	$\bar{1}11$	2.43	11	110	110
8	011	2.52	9	14	102	8.59	15	6	201	4.33	18	8	$1\bar{1}1$	3.27	17	$\bar{1}11$	$1\bar{1}1$
10	210	3.12	11	7	$1\bar{1}2$	10.51	20	12	$1\bar{1}2$	5.19	26	11	111	4.15	23	101	011
11	$1\bar{1}0$	3.17	12	8	$\bar{1}12$	12.55	23	9	201	5.29	28	10	$22\bar{1}$	4.17	24	$\bar{2}01$	$0\bar{2}1$
12	$0\bar{1}2$	4.21	18	12	$1\bar{1}4$	20.75	47	13	$2\bar{2}1$	8.20	45	12	$\bar{2}2\bar{1}$	5.75	37	$\bar{1}21$	$\bar{2}11$
13	$0\bar{2}1$	5.04	24	10	310	38.50	99	10	310	9.62	58	13	$\bar{1}12$	6.82	49	$\bar{2}12$	$\bar{1}22$
14	102	5.20	26	11	$3\bar{1}0$	38.87	103	11	$3\bar{1}0$	9.72	61	14	$\bar{1}30$	6.90	50	120	210

N.B.—For Lattices (V) and (VI) the form number and rank are the same as for lattice (I). The value of S^2 in lattices (V) and (VI) is obtained by multiplying the S^2 of (I) by constant factors.

occupied in the complete list. Table 4 will permit comparison between the various lattices considered.

We observe that (except in lattice I) the order departs widely from the observed order of importance (**1** to **14**). Moreover, the known forms are among the first 26 in the first lattice, compared with the first 103, 61, and 50 in the other lattices. This shows how ill-adapted to the facts would be such unit-cells as (II) and (III).

Pseudo-symmetry

It is often said to be advantageous to choose a particular set of axial elements in order to stress a certain pseudo-symmetry possessed by the crystal. This practice, however, is to be condemned when the unit-cell adopted to emphasize the pseudo-symmetry ignores the Law of Bravais.

Of this, the present study affords a striking example. It so happens that our crystals sometimes exhibit a pseudo-tetragonal symmetry, due to nearly equal development of the forms **1** and **2**. Let us project the crystal on a plane perpendicular to the zone axis

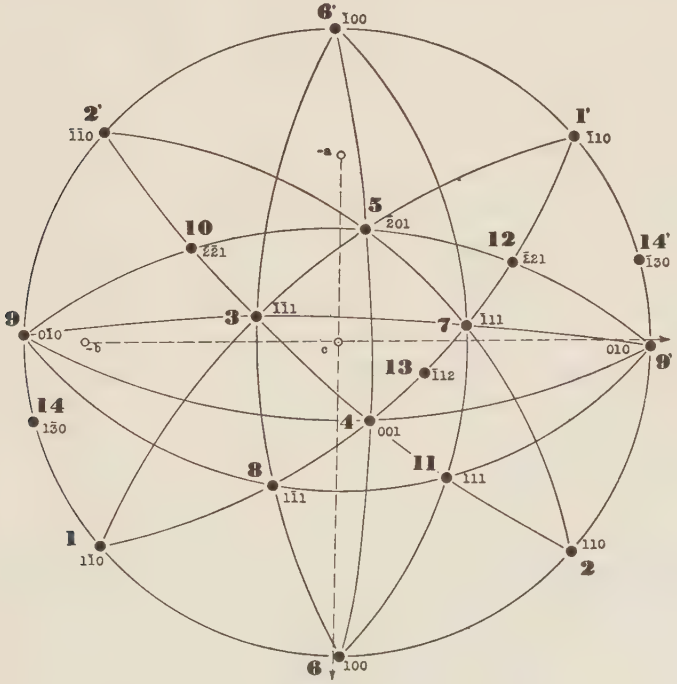


Fig. 2. Projection IV.

(1, 2). We see (Fig. 2) that the projection has a somewhat distorted tetragonal appearance, if we take the main faces only into account. It also shows the presence of a plane of pseudo-symmetry: the great circle **4, 5.** It must of course be observed that face **13** has no symmetrical equivalent on the left side of the projection (Fig. 2) and that neither **14** ($1\bar{3}0$) nor **14′** ($\bar{1}30$) is reflected in the plane of pseudo-symmetry. Nevertheless, the pseudo-symmetry is a fairly well marked feature. The question arises: Is it advisable to express this property by choosing a unit-cell *ad hoc?*

The following set of axial elements (see projection IV, Fig. 2) would answer that question:

$$\begin{aligned} &\breve{a}:\bar{b}:\dot{c}=1.2708:1:0.7580,\\ &\alpha=101°57',\quad \beta=118°55',\quad \gamma=85°13', \qquad \text{(IV)}\\ &A=78°59',\quad B=61°26',\quad C=88°53'. \end{aligned}$$

This set of elements is derived from the same five fundamental angles as the other sets, by using the symbols **4**(001), **6**(100), **2**(110), **1′**($\bar{1}10$), and **3**($\bar{1}\bar{1}1$).

The transformation formulae from the first system to this one are:

$$h^{IV}=h'-l',\ k^{IV}=h'+l',\ l^{IV}=-k'.$$

The face symbols emphasize the pseudo-tetragonal symmetry as the forms **1** and **2,** on the one hand, and **6** and **9,** on the other, have the same indices. The presence of the plane of pseudo-symmetry is also brought out by the fact that **10** and **12, 3** and **7, 8** and **11** have similar symbols.

But when we list the forms in their order of decreasing reticular densities or increasing S^2 (Table 4), we realize that this new set (IV) of axial elements does not give a proper expression to the observed facts concerning the importance of faces. In the lattice defined by (IV) the Law of Bravais does not hold much better than in (II) or (III). Does this invalidate the law? No. It merely proves that the choice of the lattice is not proper. The Law of Bravais is independent of any theory, it is a law of observation which no new theory can disregard.

Are There Other Solutions?

If we turn the stereographic projection IV (Fig. 2) in its plane, and keep the same five fundamental angles but adopt the symbols **3**(001), **2′**(100), **1**(010), **6**($\bar{1}10$), and **4**($\bar{1}01$), we obtain a new projection and the following set of axial elements:

$$\begin{aligned} &\breve{a}:\bar{b}:\dot{c}=1.0473:1:0.9786,\\ &\alpha=105°14',\quad \beta=115°22',\quad \gamma=89°54', \qquad \text{(V)}\\ &A=\ 73°\ 9',\quad B=\ 63°40',\quad C=82°42'. \end{aligned}$$

If we list the forms of this lattice according to decreasing reticular densities and italicize the known forms, we get exactly the same results as in case (I) (see Table 4): all the known forms appear at the same places in the list, although with other symbols. The transformation formulae to pass from (I) to (V) are:

$$h^V = -h' + k', \; k^V = -l', \; l^V = -k'.$$

The values of S^2 in lattice (V) are exactly proportional to those of lattice (I). Denoting by $S(\mathrm{I})$ and $S(\mathrm{V})$ the reticular areas in lattices (I) and (V) respectively, we may write

$$S^2(\mathrm{V}) = K \cdot S^2(\mathrm{I}),$$

with $K = 0.917$.

Is this new solution (V) distinct from (I)? In other words does unit-cell (V) define the same lattice as unit-cell (I)? Or again, is the volume of unit-cell (I) equal to the volume of unit-cell (V)?

The formula giving the cell volume may be written as follows: $V = abc \sin\beta \sin\gamma \sin A = abc \sin\gamma \sin\alpha \sin B = abc \sin\alpha \sin\beta \sin C$ for any given lattice. The unit of volume is the cube of the parameter b.

Before any two cell volumes can be compared, it must be determined that the unit in which the volumes are expressed is the same for both cells.

The Three Proportional Unit-Cells

It must be kept in mind that it is possible to express the volume of a given unit-cell in three different units, *viz*, the cubes of the three unit-lengths. The volume will be expressed by the smallest number when the largest unit-length is taken as $\bar{b}$, or in other words when, the unit-length of $\bar{b}$ being conventionally taken as unity, the unit-lengths of $\breve{a}$ and $'$ are both less than unity.

As an example, let us consider (Fig. 3) the three axes of reference

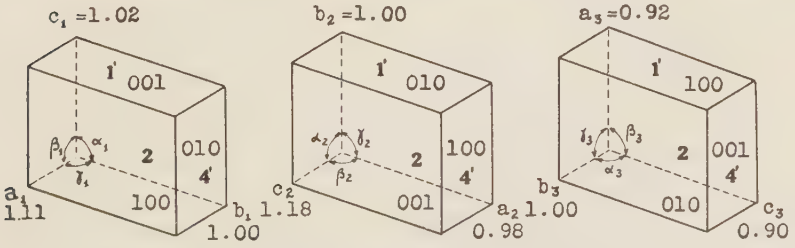


Fig. 3. Cyclic permutations of the axial elements in the first octant. (N.B.—All three cells are purposely oriented in parallel positions so as to show the proportionality of the volumes.)

Oa, Ob, and Oc in our first lattice (I). The corresponding unit-lengths are

$$\breve{a}_1 : \bar{b}_1 : \dot{c}_1 = 1.1082 : 1 : 1.0219.$$

But we may choose any one of the three lengths as unit $\bar{b}$, if we change the names of the axes according to the proper cyclic permutation (leaving the system of reference right-handed). The above values, for instance, may be divided by 1.0219 and called $\dot{c}_2$, $\breve{a}_2$, $\bar{b}_2$ or divided by 1.1082 and designated $\bar{b}_3$, $\dot{c}_3$, $\breve{a}_3$, which leads to the two possibilities:

$$\breve{a}_2 : \bar{b}_2 : \dot{c}_2 = 0.9786 : 1 : 1.0845,$$
$$\breve{a}_3 : \bar{b}_3 : \dot{c}_3 = 0.9221 : 1 : 0.9023.$$

It is easy to see that the angles α, β, γ between the axes follow the same cyclic permutation, as do also the angles A ($010 \wedge 001$, B ($001 \wedge 100$), and C ($100 \wedge 010$).

Let

$$\alpha_1 = 105°14', \quad \beta_1 = 103°37', \quad \gamma_1 = 60°45',$$
$$A_1 = 79°58', \quad B_1 = 82°42', \quad C_1 = 117° 4'$$

be the values of these angles in the case of unit-cell (I), we have

$$\alpha_2 = \beta_1 \quad \beta_2 = \gamma_1, \quad \gamma_2 = \alpha_1,$$
$$A_2 = B_1, \quad B_2 = C_1, \quad C_2 = A_1;$$

and

$$\alpha_3 = \gamma_1, \quad \beta_3 = \alpha_1, \quad \gamma_3 = \beta_1,$$
$$A_3 = C_1 \quad B_3 = A_1 \quad C_3 = B_1.$$

From the above, it is clear that the volumes of the three cells will be in the ratio:

$$V' : V'' : V''' = a_1 b_1 c_1 : a_2 b_2 c_2 : a_3 b_3 c_3,$$

or, in the present instance,

$$V' : V'' : V''' = 1 : \left(\frac{1}{1.0219}\right)^3 : \left(\frac{1}{1.1082}\right)^3.$$

The three expressions of the cell volume in lattice (I) are:

$$V'(\mathrm{I}) = 0.945, \quad V''(\mathrm{I}) = 0.886, \quad V'''(\mathrm{I}) = 0.694.$$

The same lattice is defined by any one of these three cells.

Identity of Lattices (I) and (V)

We find the following three expressions for the volume of cell (V):

$$V'(\mathrm{V}) = 0.886, \quad V''(\mathrm{V}) = 0.945, \quad V'''(\mathrm{V}) = 0.771.$$

The volume of cell (I) and that of cell (V) are expressed by the same number 0.886 when the unit of length is the same in both cases, as can be easily ascertained.

It follows that the two unit-cells (I) and (V) define the same lattice (Fig. 4). It may happen that the Haüy-Bravais lattice is not definitely determined, that is to say one may, in certain cases,

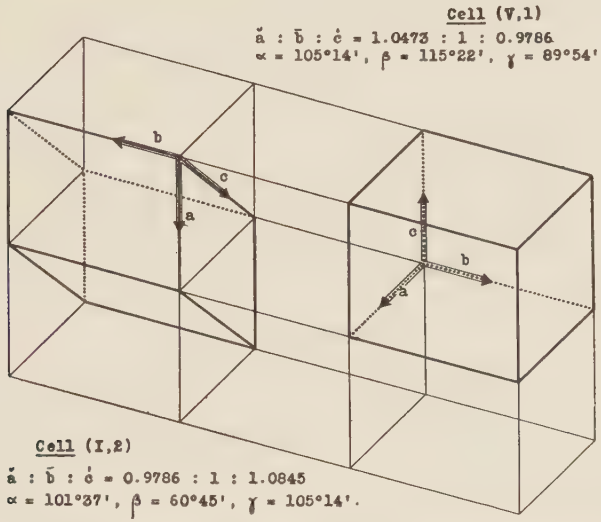


FIG. 4. Relationship between cells (I,2) and (V,1) which define the same lattice. (N.B.—The axial elements of cell (I, 2) are obtained from cell (I, 1) by the first cyclic permutation as explained above.)

hesitate between two or more lattices which comply equally well with the Law of Bravais. In this study we have not found any lattice, other than (I), to be in agreement with the Law of Bravais.

Choice of the Unit Cell Defining the Haüy-Bravais Lattice

It may be interesting to observe that cell (V) brings out the remarkable value $\gamma = 89°54'$.

From the point of view of simplicity of indices, we see that the face symbols are simpler with cell (I) than with cell (V). In the former, all the known faces are found in the first four series, that is to say among 25 symbols containing either (0, 0, and 1), (0, 1, and 1), (1, 1, and 1), or (0, 1, and 2). With cell (V), the known faces occur among the 49 of six series, including the symbols formed with (1, 1, and 2), or (2, 2, and 1). (See Table 5.)

TABLE 5

SERIES OF EQUALLY SIMPLE FORM SYMBOLS LISTED ACCORDING TO DECREASING DENSITIES IN SYSTEMS (I), (V), AND (VI)

(I)	*001*	*100*	*010*									
	110	*$\bar{1}$01*	*0$\bar{1}$1*	*101*	*011*	*1$\bar{1}$0*						
	$\bar{1}\bar{1}$1	111	1$\bar{1}$1	$\bar{1}$11								
	210	120	*0$\bar{1}$2*	$\bar{1}$02	$\bar{2}$01	*0$\bar{2}$1*	*102*	201	012	021	2$\bar{1}$0	$\bar{1}$20
(V)	*010*	*100*	*001*									
	10$\bar{1}$	*1$\bar{1}$0*	*1$\bar{1}$0*	*110*	011	*101*						
	$\bar{1}\bar{1}$1	*$\bar{1}$11*	11$\bar{1}$	111								
	$\bar{2}$01	02$\bar{1}$	$\bar{1}$02	1$\bar{2}$0	$\bar{2}$10	0$\bar{1}$2	*120*	210	021	012	201	102
	$\bar{1}\bar{1}$2	$\bar{2}\bar{1}$1	*$\bar{1}\bar{2}$1*	$\bar{2}$11	1$\bar{2}$1	$\bar{1}$21	1$\bar{1}$2	$\bar{1}$12	2$\bar{1}$1	121	211	112
	$\bar{2}\bar{1}$2	$\bar{1}\bar{2}$2	$\bar{2}$12	$\bar{2}\bar{2}$1	$\bar{2}$21	1$\bar{2}\bar{2}$	2$\bar{2}$1	$\bar{1}$22	2$\bar{1}$2	221	122	212
(VI)	*100*	*010*	*001*									
	0$\bar{1}$1	*$\bar{1}$01*	*1$\bar{1}$0*	*110*	101	*011*						
	$\bar{1}\bar{1}$1	*$\bar{1}\bar{1}$1*	$\bar{1}$11	111								
	0$\bar{2}$1	$\bar{2}$01	0$\bar{1}$2	2$\bar{1}$0	$\bar{1}$20	$\bar{1}$02	*210*	120	201	102	021	012
	$\bar{1}\bar{1}$2	$\bar{1}\bar{2}$1	*$\bar{2}\bar{1}$1*	1$\bar{2}$1	$\bar{2}$11	2$\bar{1}$1	$\bar{1}$12	1$\bar{1}$2	$\bar{1}$21	211	121	112
	$\bar{1}\bar{2}$2	$\bar{2}$12	1$\bar{2}$2	$\bar{2}\bar{2}$1	2$\bar{2}$1	$\bar{2}$12	$\bar{2}$21	2$\bar{1}$2	$\bar{1}$22	221	212	122

N.B.—Known forms are italicized.

But there are innumerable unit-cells, with different shapes, defining the same lattice, such as unit-cells (I) and (V) in the present instance. Which one should be adopted? There is no definite rule relative to this matter, except in certain cases of pseudo-symmetry.[6]

We adopt the unit-cell which has the smallest primitive translations (or parameters $\breve{a}$, $\bar{b}$, $\dot{c}$). One must be careful to measure the translations to be compared in terms of the same unit of length (Fig. 4). An easy rule to follow to see whether a given unit-cell should not be replaced by some other having shorter primitive

[6] In the case of *epidote*, for instance, G. Friedel shows that the usually adopted axial elements:

$$\breve{a}:\bar{b}:\dot{c}=1.5787:1:1.8036, \quad \beta=64°37',$$

although correctly defining the Haüy-Bravais lattice are poorly chosen because they do not bring out the remarkable pseudo orthorhombic symmetry.

He suggests to refer epidote to the following system of axes: new a-axis = old [$\bar{1}$00], new b-axis = old [010], new c-axis = old [102] and to center face (010). The new axial elements:

$$\breve{a}:\bar{b}:\dot{c}=1.5787:1:3.2590, \quad \beta=89°26',$$

stress the pseudo-symmetry ($\beta=89°26'$) as the faces which have nearly equal reticular densities are denoted by similar face symbols. (G. Friedel, *op. cit.*, p. 140.)

translations is to calculate the lengths of the face-diagonals and body-diagonals of the first cell. If any diagonal is found that is shorter than one selected for the primitive translations, then this diagonal should be taken as a parameter and substituted for the largest of the original translations.

Let us compute the diagonals of cell (I, 2) in which the unit length $\bar{b}$ is the same as in cell (V, 1). Graphically, by obliquely projecting all the lattice points of (I) onto a plane of the cell (I, 2), the projecting lines being parallel to the zone axis defined by the other two cell faces, it can be determined whether a face diagonal is shorter than any of the original translations. In case of doubt, or for accurate determination, the distance formula is used. The latter can be written as follows:

$d^2 = u^2a^2 + v^2b^2 + w^2c^2 + 2\ uv \cdot ab \cdot \cos\gamma + 2\ vw \cdot bc \cdot \cos\alpha + 2\ wu \cdot ca \cdot \cos\beta$,

where d is the parameter of a lattice row $[uvw]$, and the row indices u, v, w are supposed to be cleared of common factors.

We reach the conclusion that one diagonal of cell (I, 2) is shorter than one of the cell translations. The face diagonal of face **1**, whose symbol is (010), when referred to (I, 2), is found to be equal to 1.0473. The new cell should then be constructed on this diagonal (1.0473) and the two smallest original translations, 0.9786 and 1. It is found to be identical with cell (V).

Cell (V) is, therefore, chosen to define the Haüy-Bravais lattice in preference to (I).

The Eight Octants in a Triclinic System of Reference and the 24 Possible Expressions of the Same Unit Cell

The three triclinic axes of reference are the intersections of the three co-ordinate planes in a Cartesian system of oblique co-ordinates. Three such planes divide space into eight octants. The first octant is defined as that formed by the positive directions of the three axes. We may take any of the eight octants for our first octant if we give proper signs to the axes.

The eight possibilities may be visualized by considering (Fig. 5) the primitive parallelopiped (V). The origin of the co-ordinates may be taken at any one of the eight corners, the three edges intersecting at that corner being taken as axes. Moreover, at each corner, there are three possible cyclic permutations (leaving the system of reference right handed), hence a total of 24 possible ways of expressing the axial elements of the same unit cell.

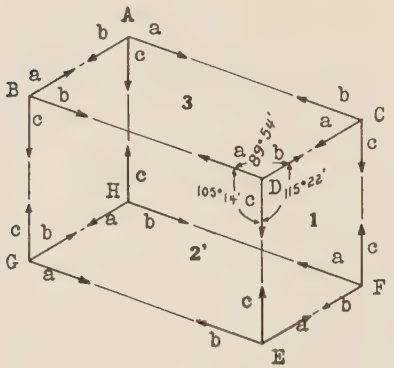


FIG. 5. The eight octants in a triclinic system of reference.

How to Limit the Choice

The axis of the main zone will be placed vertically. This axis is represented by the intersection of the two most important forms: in the present case, **1** and **2**. This condition reduces the number of possible expressions to eight. The origin of the co-ordinates being taken at any corner of the cell (*A*, *B*, *C*, *D*, *E*, *F*, *G*, or *H*), the choice of one axis (here the $\dot{c}$-axis) uniquely defines the system of reference, which must be right handed.

If it is desired to have the $\breve{a}$-axis sloping down toward the observer, then the angle β must be greater than 90°. Among the four different values which β may assume in the eight reference systems now being considered, two are greater than 90° (105°14′ and 115°22′), the other two are their supplements. This new condition reduces the number of possible expressions to four (corners *B*, *D*, *G*, or *H*).

Now if the unit lengths $\breve{a}$ and $\bar{b}$ are so chosen that $\breve{a}$ is the shorter (as in the orthorhombic system), we are left with only two possible sets of axes (*G* and *D*) out of the four. Their interaxial angles are:

$$\alpha = 64°38', \qquad \beta = 105°14', \qquad \gamma = 90°\ 6',$$

and

$$\alpha = 115°22', \qquad \beta = 105°14', \qquad \gamma = 89°54'.$$

The latter set (corner *D*) is selected in order that the stereographic projection of the basal pinacoid may fall in the lower right quadrant of the primitive circle.

Final Set of Axial Elements

The parameters are proportional to those of cell (V) divided by 1.0473.

$$\breve{a}:\bar{b}:\frac{1}{c}=0.9548:1:0.9344,$$

$$\begin{array}{lll} \alpha=115°22', & \beta=105°14', & \gamma=89°54', \\ A=\ 63°40', & B=\ 73°\ 9', & C=82°42'. \end{array} \qquad \text{(VI)}$$

The transformation formulae

$$h^{VI}=-l',\ k^{VI}=k'-h',\ l^{VI}=-k',$$

give the symbol $(h^{VI}k^{VI}l^{VI})$ of a face in system (VI) when its indices $(h'k'l')$ are known in system (I).

The new orientation is seen in the stereographic projection (VI), (Fig. 6).

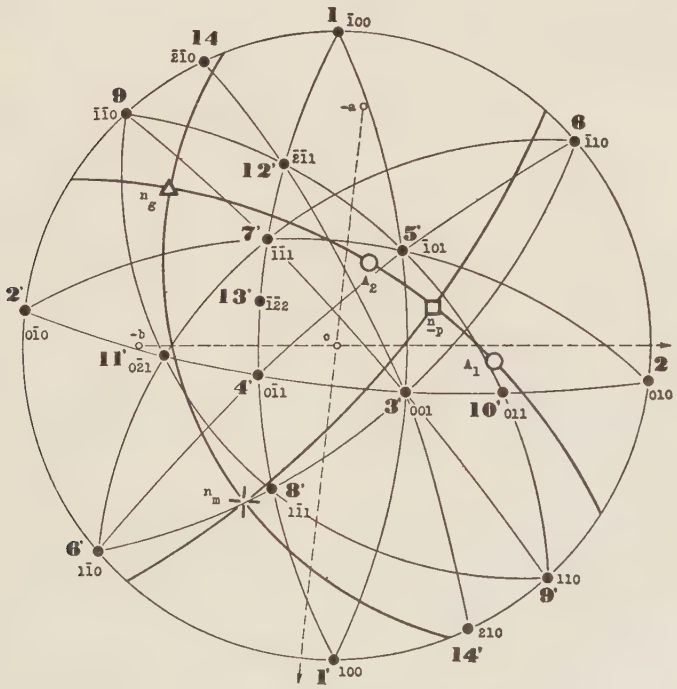


Fig. 6. Projection VI.

PART II. CRYSTALLOGRAPHIC DATA FOR SODIUM MOLYBDO-TELLURATE

General. This new compound has the following *chemical formula*, according to Professor S. R. Wood who prepared it:

$$3\ Na_2O \cdot TeO_3 \cdot 6\ MoO_3 \cdot 22\ H_2O.$$

Its *specific gravity* is 2.58 ± 0.02. Due to the solubility of the substance in water, the specific gravity was determined in ether and corrected for water.

The *hardness* is $2\frac{1}{2}$.

Sodium molybdo-tellurate crystallizes readily from a water solution forming perfectly developed small crystals, ranging in size from one millimeter or less to about five millimeters in cross section. The faces of a crystal will whiten and lose their reflecting power if left too long in dry, warm air.

Form. The crystals belong to the pinacoidal or holohedral class of the triclinic system (Fig. 7).

The axial elements are:

$$\breve{a} : \bar{b} : \dot{c} = 0.9548 : 1 : 0.9344,$$

$$\alpha = 115°22', \qquad \beta = 105°14', \qquad \gamma = 89°54',$$

$$A = 63°40', \qquad B = 73°\ 9', \qquad C = 82°42'.$$

Fourteen forms have been observed. They are in order of their importance: $h^1\{100\}$ and $g^1\{010\}$, $p\{001\}$ and $e^1\{0\bar{1}1\}$, $a^1\{\bar{1}01\}$ and $m\{1\bar{1}0\}$, $b^{1/2}\{\bar{1}\bar{1}1\}$ and $d^{1/2}\{1\bar{1}1\}$, $t\{110\}$, $i^1\{011\}$, $e^{1/2}\{0\bar{2}1\}$, $\{\bar{2}\bar{1}1\}$, $\{\bar{1}\bar{2}2\}$, $\{210\}$. The last three forms are very rare.

The faces are numbered in order of their importance on the stereographic projection (Fig. 6). The list of faces according to decreasing reticular densities can be found in Table 4 (last column).

Interfacial angles: the list of measured and computed angles is given in Table 1.

Habit. Usually tabular parallel to either $h^1\{100\}$ or $g^1\{010\}$, the crystals also, though more rarely, exhibit a short prismatic habit together with a pseudo-tetragonal appearance due to equal development of $h^1\{100\}$ and $g^1\{010\}$. The main zone, or zone of elongation, is almost invariably [001] defined by the same two forms. Probably all the faces of this zone are striated; the striations, however, are most distinctly visible on $h^1\{100\}$ and $g^1\{010\}$, usually better on the former than on the latter, and also on $p\{001\}$.

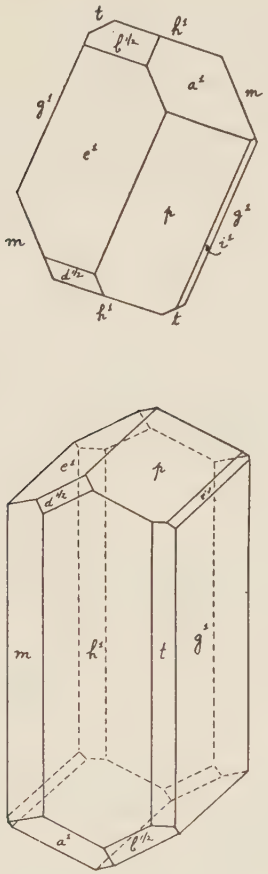


FIG. 7. A typical crystal of sodium molybdo-tellurate showing the ten principal forms, the usual prismatic habit, and a tendency towards pseudo tetragonal symmetry. (Horizontal plan and clinographic projection in the standard position: 18°30′ rotation and 9°30′ tilt. Drawn from the stereographic projection VI, Fig. 6.)

The crystals usually show a number of modifications. Some faces may be slightly hopper-shaped. This has often been observed for the face on which the growing crystal lies at the bottom of the crystallizing vessel.

CLEAVAGE, GLIDING, TWINNING. None of these discontinuous vectorial properties could be detected.

OPTICAL DATA. The sodium molybdo-tellurate crystals are colorless to whitish, transparent to translucent, with vitreous luster.

The crystals are biaxial and negative. $n_p = 1.577$, $n_m = 1.662$, $n_g = 1.683$; all three indices ± 0.003. $2V = 50\frac{3}{4}° \pm \frac{3}{4}°$.

The optical orientation is as follows:

Angle	$h^1(100)$	$g^1(010)$	$p(001)$	Φ	Λ
n_p	$102\frac{1}{2}°$	$58\frac{1}{2}°$	$29\frac{1}{2}°$	$331\frac{1}{2}°$	$36\frac{1}{2}°$
n_m	42°	110°	63°	$114\frac{1}{2}°$	$59\frac{1}{2}°$
n_g	129°	140°	$102\frac{1}{2}°$	216°	$72\frac{1}{2}°$
A_1	$85\frac{1}{2}°$	36°	30°	359°	54°
A_2	$119\frac{1}{2}°$	82°	47°	285°	$32\frac{1}{2}°$

The first meridian is passed through the pole (010). Longitudes represented by Φ are measured clockwise. The Λ values designate colatitudes.

The extinction angle, measured against the edge between $h^1(100)$ and $g^1(010)$, is

on $h^1(100) = 34°$, on $g^1(010) = 17°$.

The optical orientation is plotted on projection VI (Fig. 6).

Dispersion: $\rho > v$. The dispersion is greater for one axis than for the other.

Optical Measurements. A fair biaxial figure can usually be obtained in convergent light, simply by examining a few crushed fragments.

The refractive indices were determined partly by the ordinary immersion method, partly by calculation, as follows:

(1) By immersion. We found that n_p had a value between 1.560 and 1.591. The relief is high in monobrombenzol (1.560) and very low in trihydrobromine (1.591); n_m is slightly above 1.650 (α-monobromnaphthalene); n_g is intermediate between 1.650 and 1.74 (methylene iodide), with a higher relief in the latter than in the former.

(2) By measurement of double refraction. The difference between $n_g - n_m$ was measured four times by means of a Berek compensator, with an average value of 0.021.

(3) By measurement of 2V. The axial angle was measured on the Fedorov universal stage.

(4) By calculation. The size of 2V was computed for several sets of values assigned to the indices within permissible limits, in agreement with the above listed observations. For a given n_p, there is

only one value of n_m which leads to $2V = 50\frac{3}{4}°$ (as $n_g = n_m + 0.021$). The curve of n_m plotted against n_p provides two values (n_m, n_p) when 2V is kept constant and equal to $50\frac{3}{4}°$. We now make use of the observation that n_p shows the same amount of relief in 1.591 as n_m in 1.650. The point on the curve which is equally distant from $n_p = 1.591$ and $n_m = 1.650$ is easily located. Its coordinates are the values adopted for n_p and n_m.

The formula, $\tan V = \frac{n_p}{n_g}\sqrt{\frac{n_g^2 - n_m^2}{n_m^2 - n_p^2}}$ leads to $2V = 50°40'$ for the adopted set of indices.

The optical orientation was determined by measuring the angles which the directions of the principal refractive indices and optic axes make with the three unit faces. The measurements obtained on the universal stage are listed in the first three columns of the table. The longitudes and colatitudes were measured on a large scale stereographic projection.

The two extinction angles given above (34° and 17°), measured with the microscope, check the values read from the stereographic projection ($33\frac{1}{2}°$ and 16° respectively).

PHOTOGRAPHY FOR THE MINERALOGIST

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INTRODUCTION

It has been said that one good illustration reveals more information than a page of description. It is important, therefore, for a mineralogist to be able to photograph geologic scenes, specimens showing structure or texture, or microscopic detail in a manner that will clearly illustrate the actual condition. To do this he must have at his command a knowledge of the photography of colored objects. He must be able to use light filters and color sensitive emulsions correctly.

The use of light filters, of various types of films or plates, of cameras, and of artificial illumination often causes considerable trouble in the minds of inexperienced operators. It is hoped that the following paper will be helpful in clarifying some of the difficulties so commonly encountered.

Publications of the Eastman Kodak Company will be referred to freely in this article. Appreciation is also expressed to Dr. G. M. Schwartz, Dr. Hans Froberg, and other members of the Geological Department of the University of Minnesota for many helpful suggestions.

LIGHT. In photography a few fundamental facts regarding light are important and must be kept in mind. The color of a light ray is determined by its wave length. The blue-violet rays have the shortest wave length, ranging from 400 and 500 $\mu\mu$ (millionths of a millimeter), while green varies between 500 and 600, and red between 600 and 700 $\mu\mu$.

The velocity of light depends upon the medium through which it travels. Light travels at the rate of about 186,000 miles per second in air and about one-third slower in glass. On passing through a triangular prism the short waves are retarded more than the longer ones; hence they are refracted to a greater extent, and white light is spread into its components forming the visible spectrum.

All of the rays contained in white light are not visible to the naked eye. The ultra-violet rays, beyond the blue portion of the visible spectrum, are short rays which are highly effective chemically. The x-rays, although not thought to be present in ordinary

white light, are still shorter than the ultra-violet rays and are also invisible to the human eye. Rays extending beyond the red end of the spectrum are known as infra-red or heat rays. These also are invisible.

Color as Recorded by the Eye

A point to be considered is the comparative sensitivity of the eye and the photographic plate. One should keep in mind the fact that nearly all of the photographic emulsions used are most sensitive to the blue rays, while the human eye seems to be most sensitive to the yellow green rays, with the color sensitiveness diminishing towards the red and the blue ends of the spectrum. If in a dark room the colors of the spectrum are increased in intensity from total darkness to visibility of the entire range, the eye would first recognize light without color, then yellow-green followed by orange and blue, then red and finally blue-violet.

Objects may appear colored in white light if they absorb any of the three principal components of the spectrum. That is, if an object is blue, it absorbs the green and red rays in white light and reflects the blue; if green, it absorbs blue and red and reflects the green; and if red, it absorbs the blue and green and reflects the red.

In general, red objects seem to be brighter to the eye than any other color. This is because red objects generally reflect a greater amount of light than the blue or green. Eastman gives the results of measurements of the light transmission of a number of colored gelatine filters as follows:

Red filters transmit about 75%–80% of red light.
Green filters transmit about 33% of green light.
Blue filters transmit about 12% of blue light.
Yellow filters transmit about 85% of yellow light.

Light Filters

It is possible by the use of transmitting or absorbing media to control the color of light. Light filters which are either colored solutions or gelatin films are used for this purpose. Such filters absorb certain colors and transmit the remaining colors of the spectrum.

The red filter when placed across the path of a beam of white light will absorb the blue and green rays allowing only the red rays to pass through. A blue filter will transmit blue and will absorb the red and green rays, while a green filter absorbs both red and blue.

In the study of light, red, green, and blue are spoken of as the primary colors.

If one of the primary colors is transmitted and the other colors absorbed, then the absorbed colors are said to be complimentary to the transmitted one. To illustrate, if blue light is absorbed, mixtures of green and red light (yellow colored light) are transmitted. The K series of filters and the G filter, of the Wratten series, absorb blue rays and give forth yellow light. The yellow is said to be complimentary to the blue. Red, therefore, is complimentary to the blue and green, and green is complimentary to red and blue, a color known as magenta.

Sensitive Emulsions

There are various types of films and plates used in photography. The ordinary film or plate has an emulsion that is sensitive only to the ultra-violet, violet, and blue rays, and does not react to red or green light. It is, so to speak, color blind. If an object which is red or green is photographed, it will appear black or dark gray on the print. Ordinary materials, such as Eastman Commercial Films, give the same monochrome rendering of colored objects that we see when we look through the deep blue C filter.

The orthochromatic film, commonly used in a photomicrograph, is not as color blind as the ordinary film. The ortho film is similar to the ordinary film but is more sensitive, or color-corrected, towards the green portion of the spectrum. As the film is still most sensitive to the blue rays, a filter will be necessary to absorb some of the blue light and allow time for the green light to react upon the emulsion. When a yellow filter is used, the film reproduces the yellows and greens, and the various colors are recorded in nearly the same monochrome values that we see when looking through the green (B) filter. If red is photographed, it will appear black or dark gray on the print.

The panchromatic emulsion is sensitive to the entire visible spectrum; thus, even red objects may be photographed in intensities as recorded by the eye. Also, this emulsion is still supersensitive to the blue portion of the spectrum; therefore a filter of the K series is used to subdue the blue rays.

If the color sensitiveness of the three types of emulsions are plotted, they would appear about as shown in figure 1.

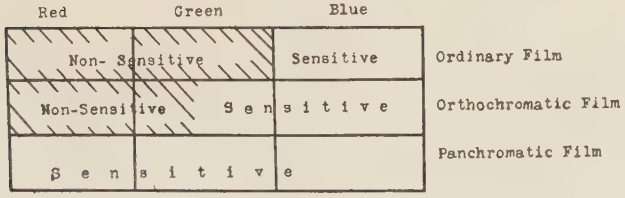


FIG. 1

USE OF FILTERS

Filters are used for three main purposes; (*a*) to make corrections for the blue super-sensitiveness of the emulsions, thus rendering color in shades of gray equal to the intensity of the color as seen by the eye; (*b*) to photograph detail on a colored object; and (*c*) to record contrast between colored surfaces.

If panchromatic films or plates are used to photograph colored surfaces or outdoor pictures, a K_3 filter will give full color correction. A K_2 filter will give good results with ortho films. Blackwelder[1] has used a dark blue filter for photographing sand dunes and white formations. A G filter is used when the field is excessive in yellow and contrast is desired, or when thick aerial haze must be penetrated. As yellow filters absorb the ultra-violet and portions of the blue rays, longer exposures can be given to allow the green and red rays to react upon the emulsion.

In microphotography contrast or detail in the photograph is usually more desired than true color rendering. A colored object will appear white upon the print if it is photographed in light of its own color, and any detail upon the photographed surface will show up at its maximum. That is, if yellow chalcopyrite is to be reproduced as a light colored mineral, then a K_3 or G filter should be used. If contrast is desired, such as is necessary when photographing intergrowths of two minerals, one of the minerals should be photographed in light which it reflects and at the same time the other should be photographed in light which it absorbs. This will make a white and black print which, obviously, will show maximum contrast. To do this it is necessary to pick a filter which has an absorption band in the range of color of one of the members of the intergrowth. Detail, however, is destroyed, and, if it is neces-

[1] Blackwelder, Eliot, Hint for Better Geologic Photographs: *Science*, Feb. 27, 1931, vol. **73**, No. 1887, p. 241.

sary to get contrast yet preserve detail, it may be necessary to use a different procedure. A rule which seems to be of practical value when photographing two objects of different colors is to use a filter the color of which is between the colors of the two objects on the spectrum. That is, if a blue covellite grain is next to a pink bornite area, a green filter will give contrast yet preserve any detail which may be exhibited. This procedure is known as over-correcting. When doing this it is best to illuminate the object by light towards the red end of the spectrum, because of the super-sensitiveness of the emulsions towards the blue rays. Thus, when photographing for detail, it is advisable to expose the material to rays of its own color, but for contrast, use light which it absorbs.

It is suggested that the best guide to the filter or combination of filters to be used in any particular case is the visual inspection of the objects through the filters, keeping in mind the color sensitiveness of the films to be used (red reproduces as black on ordinary films, etc.).

By following these few rules it will be possible to control the action of the photographic plates or films and obtain the desired results.

A few mineral combinations are listed below giving the required filter to be used in their photography when using ortho double-coated films or plates. One of four filters, namely the K_3 (yellow), G (dark yellow), B (green) and H (blue), should be employed.

Bornite and chalcocite	B, G is good
Bornite, chalcopyrite, and gangue	K_3 is best, G and B good
Chalcocite and pyrite	H or B
Chalcocite and galena	B
Chalcopyrite and cubanite	H
Cobaltite, niccolite, silver and gangue	H
Detail in chalcocite	B
Detail in thin sections	B
Detail on sand grains	B
Domeykite and arsenic	A (with panchromatic film)
Domeykite and arsenic	H
Pyrrhotite and gangue	H or B
Pyrrhotite and magnetite	K_3 or G

Short[2] uses five color filters with panchromatic plates—the A (red), B, (K_3), G, and H. He gives a partial list of filters used for mineral combinations.

[2] Short, M. N., Microscopic Determination of Ore Minerals: *U.S.G.S. Bull.* **825,** p. 25, 1931.

Argentite and galena, B.
Bornite and covellite, H best; B gives little contrast.
Bornite and tennantite, B.
Bornite and chalcocite, any filter will do; none required.
Bornite, chalcocite, and chalcopyrite, B.
Chalcocite and chalcopyrite, B.
Chalcocite and covellite, H.(Covellite prints dark,and constrast should be reduced.)
Mottled chalcocite, B needed.
Chalcopyrite and galena, H best; B very good.
Chalcopyrite and pyrite, H.
Gangue minerals, K_3 or G is best; with other filters transparent minerals too dark.
Specularite and magnetite, H.
Sphalerite, K_3; with other filters this mineral appears too dark.

In general, deep colored filters increase contrast. A deep yellow G filter or red A filter will give a high degree of contrast.

For general outdoor work it is desirable to have a green, a blue, a yellow, and a red filter. For ordinary and orthochromatic films, the K_3 probably is the most useful. A green Wratten B or No. 58, a blue H or No. 45, a K_2 or No. 8, and a red A or No. 25 can also be recommended.

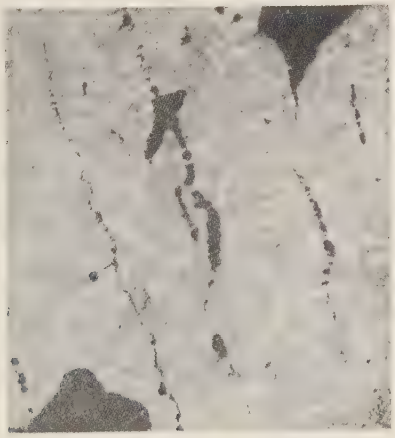


FIG. 2. Chalcopyrite (white) and Bornite (gray) intergrowth, photographed on a metallographic microscope. A K_3 filter was used with ortho cut film, also arc light illumination with a 6 second exposure through a 1 mm. opening in the iris diaphragm. Mag. 100×.

Often the expense of good filters is beyond the average pocketbook. It is easy, however, to make a series of fairly good filters by cementing pieces of colored cellophane between glass squares.

Glass from old photographic plates can be cleaned with hot water or by the use of a 4% solution of sodium fluoride, 60 grams, and 40% solution of formaldehyde, 30 cc.

The glass should be cut 2 in. by 2 in. so as to fit into standard filter holders. Some clear lacquer should be poured on a clean surface of one of the squares. Next, place a piece of cellophane on the wet lacquer and press all air bubbles and wrinkles out of the cellophane with another square. When perfectly smooth, remove the top glass square and place a few drops of clear lacquer on the cellophane. Then put the top square into place, being sure that there are no wrinkles or bubbles. It is advisable to bind the edges of the filter with thread and cover the thread and edges of the glass with lacquer. This will make the filters more permanent.

Another method for making home-made filters is to cement the colored cellophane between the two layers of cardboard leaving a hole in the center equal to the aperture desired.

A fairly complete series can be made by varying the number of layers of cellophane between the glass squares. A sky filter can be made by cementing only half of the square with yellow cellophane.

A series of home-made filters found useful are listed below. These were spectroscopically compared with Wratten filters.

4 layers of yellow cellophane	about Wratten 16, near G
2 layers of yellow cellophane	about Wratten 12, near K_3
1 layer of yellow cellophane	about Wratten 17, near K_2
1 layer of yellow and 1 of green	about Wratten 57, near B
2 layers of blue cellophane	about Wratten 41, near H
3 layers of blue cellophane	for sand dunes, grains, etc.
2 layers of green cellophane	about Wratten 66, near P

Cameras for the Mineralogist

In selecting a camera for field and general use the following points should be kept in mind: (*a*) the general cost and upkeep, (*b*) the size or bulk of the camera, (*c*) the size of the picture, and (*d*) the quality of the picture.

For general work a camera taking pictures $3\frac{1}{4}\times4\frac{1}{4}$ inches, or larger, with a 4.5, 5.6, or 6.3 anastigmatic lens, is to be recommended. In general, pictures in publications are about this size; thus, no enlarging or reducing is necessary. The camera should be focusable by a ground glass screen. A camera should be adapted to handle cut films, plates, or film pack, thus permitting the use of higher grade emulsions. The shutter arrangement on almost

every camera is suitable for geologic work, although the better class of shutters make the camera more versatile.

If pictures are to be taken in the field where equipment has to be packed for considerable distances, a small camera undoubtedly should be considered. Small cameras with high grade and extremely fast lenses, taking from sixteen, to forty pictures on a single film, are very popular for this type of work. The high grade lens produces a critically sharp negative which can be enlarged to any desirable size. Another attractive feature of a small camera is its economy. The films are inexpensive and the best pictures of a roll can be enlarged at a small cost. These cameras are also very compact and are easy to handle. The small pictures also make excellent illustrations for the field notebook.

The individual geologist has little use for motion picture cameras except to take pictures for illustrated lectures. There are times when it is desirable to have motion pictures of geologic processes in action, field trips, field methods or localities. Where a group of geologists are working together, especially at a university, there should be a motion picture camera and projector in the equipment.

Exposure of the Emulsions

The length of exposure depends upon the type of film used, the speed of the lens, and the amount of light on the object. Generally, distant scenes require less time than close subjects, while nearby shaded objects require a longer exposure than objects fully lighted by the sun. An exposure table for rectilinear and anastigmat lenses is given below.

Exposure Table for Outdoors

For $2\frac{1}{2}$ hours after sunrise until $2\frac{1}{2}$ hours before sunset on days when the sun is shining.

	Shutter Speed	Rect. US	Anast. f
Group 1—Snow, marine, beach scenes. Extremely distant landscapes	1/25	32	22
Group 2—Ordinary landscapes showing sky, with a principal object in the foreground.	1/25	16	16
Group 3—Nearby landscapes showing little or no sky-groups, street scenes	1/25	8	11
Group 4—Portraits in the open shade not under trees or the roof of a porch, shaded nearby scenes	1/25	4	7.7, 7.9

The table shows that the exposure varies with the size of aperture of the lens, otherwise known as the lens stop. Two different systems are used in naming the stops, both being based upon the ratio between the diameter of the lens opening to the focal length of the lens. The one is the Uniform System (US), and the other the F System. In the latter the stop is expressed as a fraction of the focal length (F/22 or *f*.22 etc.). That is, the aperture is 1/22 of the focal length. In the US system the numbers are proportional to the exposure required, with *f*.4 being taken as unity. A table showing a comparison of the two systems is as follows:

F	*f*.4	*f*.5.6	*f*.6.3	*f*.8	*f*.11	*f*.16	*f*.22	*f*.32	*f*.45
U.S.	1	2	2.5	4	8	16	32	64	128

This table shows the relative exposure that is required with the *f*. system stops, the exposure varying as the square of the *f*. value, so that *f*.11 requires twice the exposure of *f*.8; *f*.16 twice that of *f*.11, and so on. US 2 requires twice the exposure of US 1; US 8, 8 times that of 1.

If a filter is used, then it is necessary to give a longer exposure because a portion of the light is removed. Commercial filters are marked with a certain factor. This is the number of times it is necessary to multiply the exposure time without a filter. That is, if a filter has a factor of 7 and a picture to be taken requires 1 second without a filter, then 7 seconds would be necessary if the filter is used.

In photomicrography the time of exposure is dependent upon the numerical aperture of the lens and the magnification. The N.A. of the lens usually is marked on its side. Short[3] states that the exposure of the negative varies inversely as the square of the numerical aperture, and directly with the square of the magnification. Generally, however, the calculated exposures are too short for low magnifications and too long for high magnifications. A few trial pictures, as suggested by Short, will aid in determining the correct exposure time. If a filter is used, the filter factor should not be forgotten, otherwise the negative will be underexposed.

[3] Short, M. N. *op. cit.*, p. 27.

Artificial Light

It is often necessary to photograph objects, such as hand specimens, sand grains, polished sections, thin sections, and fossils in artificial light.

One photographing a specimen should adjust a strong light, about 200 or 500 watts, so as to illuminate one side of the object at about a 45° angle from a line between camera and subject. A light about half as strong should be placed so as to throw its light on the other side. The angle between the lights should not be over 90°. The structure and texture of a specimen must be brought out by controlling the shadows. Lights shining directly opposite each other tend to deaden the reproduction. Generally a color filter is not necessary when using incandescent lamps because the yellow lights are about the same color as light through a K_1 filter.

An arc light is an excellent illuminator. It is best used in microphotography but often comes in handy for photographing sand grains, fossils, and small objects, especially when a vertical camera is to be used. Detail in sand grains can be shown by adjusting the concentrated arc light beam to strike the grains at an angle of about 15°–25°. No other light is necessary. A blue filter or green filter will help bring out detail and control highlights.

Thin sections can be illuminated by allowing the arc light beam to strike the mirror of the petrographic microscope. A green filter or yellow filter must be used, except when the section is predominantly red.

Polished surfaces can be photographed by directing the arc light beam on to the reflecting prism in the microscope. Here again a filter must be used.

Often a projection machine can be adjusted to give a light beam like the above mentioned arc light.

Special Hints

When photographing a specimen it should be perfectly clean and free from dust. A photomicrograph of a polished surface should be made only after the surface is entirely free from deep scratches, or the polish is as perfect as can be obtained with the equipment available.

Sand grains should be thoroughly washed and dried to remove all dust particles. If a dark background is desired use a piece of dark red celluloid. See Figs. 3 and 4.

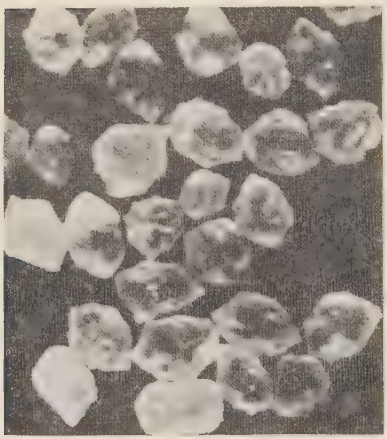


FIG. 3. These angular sand grains were photographed on a dark red celluloid sheet, giving a black background. An arc light beam strikes the grains at an angle of 15° from the horizontal. No filter is used. Enlarged 10× by use of a special lens on a vertical copy camera.



FIG. 4. Transparent sand grains photographed on a red celluloid background. The arc light strikes the grains at a low angle. Reflection of the light from the polished surfaces of the grains illuminated all sides of the grains. A green filter may be used to soften the high lights. Mag. 10×.

Dark fossils or rock specimens often need a thin white coating of ammonium chloride in order to make the features stand out.

If a banded structure does not show up as desired, the negative can be retouched by lightly building up the bands with a pencil. Remember, however, that dark areas on the negative become light areas on the print.

Processing the Negatives and Prints

Complete information on formulas can be taken from the sheet of directions inclosed in each package of films. The main points to be remembered are that panchromatic films should be developed in total darkness or in weak green light; red light of low intensity can be used for ordinary and orthochromatic films; printing out papers also can be used in red light.

The grade of paper to be used, the length of exposure, and the amount of time used in developing the print can best be learned by a few trials.

If the prints are made on glossy paper they are dried upon a ferrotype tin which has been coated and polished with paraffin and benzine to prevent the prints from sticking.

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THE ORIGIN OF THE SAND BARITES OF TH LOWER PERMIAN OF OKLAHOMA

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The presence of barite as a cementing material that forms concretions and crystal aggregates (known as "sand barites" or "barite rosettes") in the lower part of the Permian (especially the Garber formation and less commonly the Wellington formation), has been known for many years although little has been published about it. Nichols[1] described a small collection of 12 specimens in 1906. Meland[2] described those found near Norman, Cleveland County, Oklahoma, and discussed their origin. Shead[3] notes the distribution of the barite, and gives some analyses of the sand barites. Dott[4] mentions the sand barites and shows their vertical distribution within the Permian formations in his Garvin County reports. Anderson[5] also mentions their occurrence. Similar sand barites and barite concretions have been found in other countries: Bohemia, Germany, Italy, England, northeastern Africa, and Egypt. The Egyptian occurrence is described by Pogue[6] who includes brief notes of the other occurrences.

The barite discussed in this paper occurs dominantly in the Garber formation of the Enid group of the Permian, but barite occurs also in the upper part of the Wellington formation, in northeastern Cleveland County. Barite is found in the southcentral part of the state from Garvin County northeast through McClain, Cleveland, Oklahoma, and Lincoln counties. Shead reports that barite as veins and radial concretionary masses occurs also in Stephens and Comanche Counties, in the southwestern part of the state. The Garber formation consists of red standstone and shales with occasional beds of limestone, and the Wellington formation is largely shale with occasional massive sandstone layers.

[1] Nichols, H. W., Sand-barite Crystals from Oklahoma: *Geol. Pub. Field Columbian Mus.*, vol. **3**, p. 31, 1906.

[2] Meland, Norman, An unpublished master's thesis, Univ. of Okla., 1922.

[3] Shead, A. C., Notes on Barite in Oklahoma with Chemical Analyses of Sand Barite Rosettes: *Okla. Acad. of Science*, vol. **3**, p. 102, 1923.

[4] Dott, Robert H., Geology of Garvin County, Okla.: *Okla. Geol. Surv. Bull.* **40**, pp. 119–143, 1930.

[5] Anderson, G. E., Geology of Cleveland and McClain Counties, Okla.: *Okla. Geol. Sur. Bull.* **40**, p. 179, 1930.

[6] Pogue, J. E., On Sand Barites from Kharga, Egypt: *U. S. Nat. Mus. Proc.*, vol. **38**, pp. 17–24, 1911.

The stratigraphic position of the sand barites is given by Dott in his section of Garvin County. He locates barite rosettes at the base of the Garber formation and at various horizons within the next 100 feet above the base. Toward the top, another zone rich in barite rosettes occurs. The barite rosettes in the Wellington formation are in a sandstone near the top of the formation.

The Garber and Wellington formations of the central barite area are not reported as containing noticeable quantities of either gypsum or salt, although elsewhere the Wellington is salt bearing. A microscopic examination of the Garber sandstone near the barite revealed the presence of gypsum, and qualitative tests of a water solution of the sand showed calcium sulfate but no chlorides. The entire series of Permian Red Beds was once bathed in a saline solution and many parts are still sufficiently salty to make the water from them unpotable. The grains of the sand containing the barite are angular to subangular and subrounded. Angular and subangular shapes predominate. The sand grains were not very well sorted as the following mechanical analysis shows:

Mesh	Size of Mesh in mm.	Percentage of Sand Grains
48	0.295	2.67
100	0.147	65.44
200	0.074	23.64
less than 200	0.074	8.25

Hematite-coated quartz grains constitute the major part of the sand, but small grains of deep red shale are scattered all through it. Occasional grains of selenite occur, as well as some calcite. Nichols (*ibid.*, p. 33) reports orthoclase.

The Barite

The barite occurs as sand barites or barite rosettes (locally called "rock roses") and barite concretions. Both types are crystalline, but the resultant forms are extremely variable. All the sand barites and most of the barite concretions are some shade of red (at least, externally) like the enclosing sandstone. The interior of a few of the sand barites is a medium pinkish-gray. This shows that there has been some transference of the iron oxides, or that the iron oxide was leached as the barite was deposited. This point will be referred to again.

The composition of the sand barites has been determined by Nichols[7] and Shead.[8] Their analyses are given in the following table:

COMPOSITION OF OKLAHOMA SAND BARITES

	Nichols	Shead[a]
SiO_2	36.99	45.13
Al_2O_3	5.36	0.88
Fe_2O_3	0.82	0.96
MgO	0.03	0.00
CaO	0.51	0.00
H_2O	0.27	0.31
SO_3	19.20	17.87
MnO	n.d.	0.02
BaO	35.76	34.25
Organic	0.32	0.00
	99.26	99.42
Sp. gr.	3.38	3.36

[a] Specimen from S.W. $\frac{1}{4}$ of S.E.$\frac{1}{4}$ of Sec. 18, T. 9 N., R. 1 W., near Norman, Okla.

The sand varied from 37 to 45 per cent in these Oklahoma sand barites. Pogue reports from 44 to 53 per cent of sand from the Egyptian occurrences.

THE SAND BARITES. The sand barites are the more striking of the two modes of occurrence, primarily because of the rosette form they develop (Figs. 1, 4, 5). They consist of a series of tabular crystals of barite intergrown in a most intricate manner but assuming dominantly the form of a rounded cluster of crystals with a central depression. The rounded edges of the tabular barite crystals encircling this depression strikingly resemble a rose, hence the name "rosettes" or "roses" (Fig. 1). All the sand barites are aggregates of these tabular barite crystals, but the method of aggregation varies widely. Probably the most common type or aggregate consists of a large tabular crystal of barite with clusters of smaller crystals on both sides. Generally, the cluster on one side is larger (Fig. 6). The crystals rarely continue through the central plate; those on each side being independent in position and shape of those on the opposite side. The central crystal may be thin, or it may have a thickness of three-quarters inch. It usually exceeds all others in size. The typical habit of barite of developing a tabular crystal parallel to $c(001)$ is seen in these crystals. As long as the

[7] Nichols, H. W., *ibid.*, p. 34.

[8] Shead, A. C., *ibid.*, p. 104.

development along *a* and *b* axes is about equal, the crystal is equidimensional and the rosette is rounded. Development parallel to the *b* axis gives an elongated form, but this is not common and neither is it possible from the crystal shape to prove that such elongation is always parallel to the *b* axis. There is no apparent relationship in the development of the crystals in the side clusters.

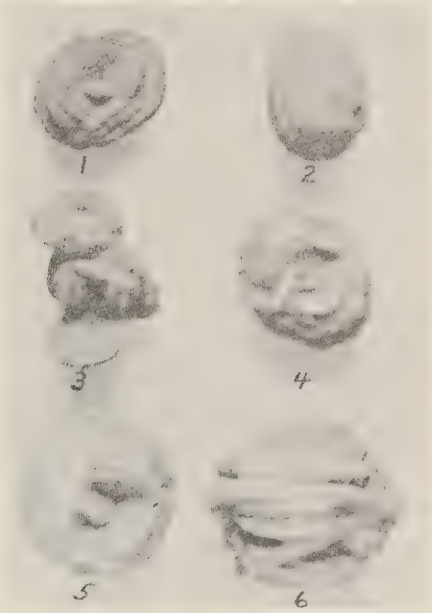


FIG. 1–6. Barite rosettes (Figs. 1, 3, 4, 5, 6) and barite concretion (Fig. 2) from Garber Formation (Permian), near Norman, Oklahoma. Fig. 1 is a typical rosette (maximum length is $2\frac{5}{16}$ inches.) Fig. 2 is a concretion. Fig. 3 shows three rosettes united irregularly. Fig. 4 shows bedding planes on the side of a vertical rosette. Fig. 5 is the top view of a horizontal rosette. Fig. 6 shows a large vertical rosette from above.

They lie in all positions (from nearly parallel to right angles) to the central crystal plate (Fig. 5), and are arranged through every possible angle in azimuth if the central plate is considered as horizontal (Fig. 1). Pogue expressed the opinion regarding the sand barites from Egypt that some of these crystals on the sides possessed the *b* axis in common with the central plate. An illustration accompanying his paper would seem to favor such an interpretation. In the Oklahoma sand barites, there does not appear to be

any crystallographic relationship, although Meland so interprets the position of some crystals. Nichols recognized that many of the side crystals were inclined about 30° to the central plate, but had he been able to study a larger suite he would have seen that their position shows all sorts of angles. The writer does not believe that one or two side crystals would develop with a definite crystallographic relationship (although this might occur) without giving rise to a more definite form than exists among these crystal clusters. These side clusters are aggregates of crystals growing irregularly just as one finds in barite vein deposits. Their rudely circular arrangement on the side of the larger crystal is a result of the physical character of the medium in which they formed.

The sand barites evidently developed in all positions in the sandstone. Using the central tabular crystal as the means of orientation, this crystal varies in position from horizontal to vertical. Where horizontal (Figs. 1 and 5), the side clusters are above and below (which position predominates is unknown, as an insufficient number were seen in place); where vertical (Figs. 4 and 6), they are on the sides. Some central crystals doubtless developed along a horizontal bedding plane, but obviously the vertical or steeply inclined rosettes did not. Their development probably followed joints. Evidence that the original bedding planes pass through the rosettes and concretions is usually seen on their surfaces (Figs. 2 and 4), and this fact was confirmed by examination of the barite in place. Where the sands were crossbedded, the central crystal might or might not follow the plane of the crossbedding but, as a rule, it did so. It is evident from these statements that the sand barites are directly related to the divisional openings (bedding planes or joints) of the sandstone, and that they were formed subsequent to its deposition. Vertical and inclined forms have different sized clusters on the two sides, as do the horizontal forms. This difference in size is probably due to variations in the source of supply of the barium salts.

The rosettes range in size from $\frac{1}{8}$ inch to several inches across the central crystal or plate. The largest seen by the writer was nearly seven inches across. The rosettes occur singly or in united forms (Fig. 3). These rosettes are regarded by geologists as horizon markers, but this criterion must be used with care, as their distribution, both vertical and horizontal, through the sandstone is very irregular, as is likewise their position within a bed.

In a massive portion of the sandstone, one group with the central plate vertical or nearly so occurred within four feet of another group in which the central plate was essentially horizontal. A few barite sand clusters occurred in the area between, otherwise it was barren.[8] These occurrences in massive sandstone show that the shape and position of the aggregate depends upon the character of the enclosing material. In another exposure, sand barites occurred dominantly along the cross-bedding planes, the central plate rudely paralleling the cross-bedding. Sand barites were irregularly distributed through other portions of the sandstone. Undoubtedly, irregularlity is the rule in the distribution of the sand barites, but where there is a control it is primarily some physical factor, such as bedding planes, cross-bedding, or variations in texture.

The internal structure of the sand barites or rosettes is simple. The crystalline barite fills the interstices of the sandstone, and some believe that the sand grains have been moved apart by the introduction of this barite cement. This is doubtful, however, as it is not in keeping with our usual concept of cementation. The barite cement was in optical continuity throughout any crystal. Adjacent crystals could be easily distinguished.

Barite Concretions. Barite concretions differ from barite rosettes in having little or no external evidence of crystals and in generally having a rounded, elliptical (Fig. 2), or irregular form. The specimens seen by the writer range from $\frac{1}{8}$ inch to 3 inches in diameter, the smaller sizes predominating. The exterior of the concretions may be rough and sandy, or pitted. Internally, these two types of concretions differ markedly. Those of the rough, sandy group are massive and are due to the cementation of the sandstone. The pitted concretions are pure barite and have a fibrous structure. The internal arrangement of the fibers is complicated. Their position is dominantly radial, but in the outer part some fibers lie nearly at right angles to each other. Instead of each fiber increasing in size outward, new ones appear that may or may not lie parallel to the longer fiber. These interesting concretions were not seen in place and their origin is not discussed in this paper. They occur in the southwestern part of the state. Their purity suggests that they were either syngenetic in origin or were replacements.

[8] The writer wishes to thank Dr. V. E. Monnett and Mr. Don Vieaux for making it possible for him to see sand barites in place in the vicinity of Norman, Oklahoma.

Origin of the Barite Rosettes

The barite rosettes are crystals or aggregates of crystals that were deposited epigenetically in sandstone. They may or may not be related to the major structural features, such as bedding planes and joints, of the beds. The crystals incorporate the sand of the sandstone. Single crystals and aggregates may occupy any position between horizontal and vertical. These facts show that the sand barites were deposited in the sandstone by solutions capable of transporting barium. The problem of their origin involves explaining (1) the source of the barium, (2) its transportation, and (3) the cause and method of its deposition as the sulfate.

Source of the Barium. Small quantities of barium are common in igneous rocks, especially those rich in feldspars, of which there are two barium varieties, celsian and hylophane. Clarke and Washington[9] give 0.055 per cent barium as the average for igneous rocks. Barium is found in other rocks as well, but not in such large quantities as in the igneous rocks. The writer collected the available evidence as to the barium in sediments[10] some years ago and was surprised to find that shales averaged about 0.05 per cent and sandstones 0.05 per cent, but that limestones contained none. Locally, barium has been reported in limestones, but these occurrences have been in mineralized regions where the barium salts were undoubtedly introduced into the limestone by mineralizing solutions.

In connection with the geological distribution of barium, the results of Failyer's[11] studies of the soils of the Great Plains are of interest. He found that the average barium content of those soils was 0.06 per cent, and that all the soils contained barium, the maximum amount being 0.11 per cent. Failyer ascribed the source of the barium to the feldspar in the clastic materials that are carried eastward from the Rocky Mountains.

It should be noted that barium is adsorbed by certain colloids, notably manganese oxide (as in psilomelane which usually shows some barium). It is not improbable that the barium of soils is also adsorbed and held by the soil colloids.

There is another possible source of the barium which should be mentioned, at least. In studies of the heavy mineral suites of the

[9] Clarke, F. W., and Washington, H. S., *Prof. Paper* **127**, p. 16.

[10] Tarr, W. A., The Barite Deposits of Missouri: *University of Missouri Studies*, Vol. III, pp. 77–80, 1918.

[11] Failyer, G. H., Barium in Soils: *U. S. Bureau of Soils, Bull.* **72**, 1910.

clastics, some have shown the presence of detrital barite. Although not a hard mineral (H = 2.5 to 3.5), barite is heavy and extremely insoluble, and so if it had not traveled too great a distance, it might well occur as a detrital mineral in sands and clays. It was shown by Lewis[12] that detrital barite occurs in the Permian sands of Central England. However, barite occurs as a cement in sandstones and less commonly as nodules in shales, and so some of the detrital grains found in well cuttings may be the result of the crushing of such a cement by the drill.

It is the writer's view that the barium found as the sulfate in the sand barites had its source (at least, *dominantly*) in the silicates within the associated sands and shales. Other sources may have been detrital grains and the barium adsorbed in any colloidal materials. The occurrence of veins of barite in the rocks about 75 miles to the southwest of the barite area under discussion suggests that there were solutions rising from below, but such a source does not seem probable for the concretions and sand barites.

Transportation of the Barium. Some barium salts are readily soluble in water, others are very insoluble in water. There can be no doubt that the barium in these concretions and rosettes was transported, because the barite cements the sand grains together. The barium might be easily transported as the chloride; less likely, as the carbonate; and only with extreme difficulty as the sulfate. The solubility in water of these salts is as follows:

Salt	Grams Soluble in 100 Grams of Water at 20°C.
$BaCl_2 \cdot 2H_2O$	26.3
$BaCO_3$	0.0023
$BaSO_4$	0.00024

It is evident at a glance that $BaSO_4$ is an extremely insoluble salt; a common statement[13] is that one part of $BaSO_4$ is soluble in 400,000 parts of water. A careful search through the literature reveals the fact that a few spring waters and an occasional well water contain barium, but these are always chloride waters. It is extremely rare that any sulfate radical is present in the solution.

A few examples of chloride waters that contain barium will be given, as they show something of the quantity present. Bischof[14]

[12] Lewis, H. P., The Occurrence of Detrital Barytes in the Permian Basal Sand at Nitticarhill: *Geol. Mag.*, vol. **60**, pp. 307–313, 1923.

[13] Gardiner, G. G., Chemical Analysis, pp. 416, 420, 1914.

[14] Bischof, G., Chemical and Physical Geology, vol. I, p. 377, 1854.

gave analyses of brines from three bore holes along the Alleghany River near Tarentum, Pennsylvania, that contained 0.91 per cent, 0.93 per cent, and 1.25 per cent of $BaCl_2$ but no sulfates. Clarke[15] gives analyses of 8 chloride waters that contain barium (Ba) in amounts ranging from 0.01 per cent to 0.82 per cent. Some of these waters contain small quantities of the radical SO_4, and some contain a large amount of CO_2. Schweitzer[16] gives an analysis of a sulfate water from central Missouri (Randolph County) that contained 2.21 grams of $BaSO_4$ in a total of 227.27 grams. This is the only sulfate water the writer knows of that contains barium. A strong chloride water from Saline County, Missouri, contained 8.15 grams of $BaSO_4$. Barium occurs in some of the brines found in oil fields. The analysis of a brine from a depth of 2,297 feet in the Bartlesville sand was furnished the writer by Mr. W. B. Wilson of the Gypsy Oil Company. It had been noted that when a sulfate water from the Ordovician formation below mingled with this brine a precipitate formed that clogged up the pipes. Mr. L. C. Case, also of the Gypsy Company, determined the precipitate to be $BaSO_4$, and upon analyzing the brine from the Bartlesville sand found 224 parts of barium per million. Barite was precipitated around the pipes in some of the wells in the Batson and Saratoga Oil Fields in Hardin County, Texas. Its source was undoubtedly the brines of the well, and the mingling of the chloride waters with sulfate waters in the casing brought about the precipitation of the barite. Very probably many natural brines would show barium if they were completely analyzed.

Spring waters, both cold and warm, deposit barite at the surface. Lindgren[17] has brought together the data relative to barium in spring deposits, and emphasizes the fact that chloride waters are the most common carriers of barium. Lindgren notes that strong carbonate waters may also hold barium in solution, even if sulfates are present. It is undoubtedly the strong brine that retains the barium even though there is a small amount of the sulfate present.

The evidence cited shows that barium is commonly transported as the chloride, and that carbonate waters may assist in keeping the barium in solution though probably not in the form of the

[15] Clarke, F. W., Data of Geochemistry, Bull. **770**, *U.S.G.S.*, pp. 186, 188.

[16] Schweitzer, P., *Mo. Geol. Sur.*, vol. **3**, pp. 233, 234, 1892.

[17] Lindgren, W., Mineral Deposits, 3rd Edit., pp. 80–88, **1928**.

carbonate. Sulfate waters, as one would expect, almost never transport barium.

It is generally known that the Permian formations of Oklahoma have been saturated with chloride and sulfate waters in the past and still contain brines in many localities. Potable waters are difficult to secure from deep or even shallow wells in many parts of the region underlain by Permian beds. The numerous salt plains of the northwestern part of the state show the presence of salt in the rocks of those regions. However, as far as the writer knows, there is no salt in the Garber formation in the area where the sand barites occur. The Garber and other formations were laid down under arid conditions, and so there is little doubt that they once contained much brine. It was this brine that dissolved the barium from the silicates, the adsorbed barium from colloids, or detrital barite from sands or clays. The more or less localized distribution of the barite suggests that certain portions of the Permian Seas were receiving sands and silts from areas locally rich in barium salts, or that the chloride waters were more efficient solvents for barium in these local areas.

Meland suggests in his hypothesis (M. A. Thesis, **1922**, p. 15) that the barium was brought into a lake by the ordinary inflow (rivers) to such bodies (an assumption unsupported by stream analyses), and that as this lake evaporated the barite was precipitated in localized areas, the precipitation occurring "in the order of insolubility of the dissolved salts." Apparently, he assumes that the sand barites were formed as the $BaSO_4$ was precipitated, an assumption that is opposed by the occurrence of the barite in the sandstone. However, that such a concentration of barium would occur in a saline body of water (however strongly chloride) is not supported by a study of the composition of any body of salt water in existence today, for none show barium nor do any of the saline deposits which were formed by evaporation in the manner outlined by Meland show barite. (See Clarke, *Bull. U. S. G. S.* **770,** Chapter 5, pp. 156–180, and chapter 7, pp. 218–260.)

It is not believed that the barium was carried far through the formation. The mode of occurrence and distribution of the barite in the sandstone indicate a comparatively nearby source for the barium. The fine-grained materials constituting the sand (or any siltstone) would favor the solution of the barium from any of the

materials in which it occurred. The solutions that carried the barium as $BaCl_2$ moved through the uniform sands in all directions, but also followed any type of divisional opening that occurred in the rocks.

Precipitation of the Barite. If the mode of transportation of the barium as the chloride (which appears to be the only feasible method) is accepted, the precipitation is a relatively simple matter as the marked insolubility of barium sulfate would favor its being deposited whenever and wherever sufficient sulfate was present. The utilization of $BaCl_2$ as the precipitating agent in testing for sulfates, even in traces, is sufficient authority for the certainty of this reaction. As small a quantity of the SO_4 radical as 0.001 per cent can be detected by this method. The addition of H_2SO_4 to a solution containing barium will detect 0.0001 per cent of barium. The delicacy of this reaction and the insolubility of $BaSO_4$ would cause the precipitation of any barium in solution. When a little sulfate is present in chloride waters along with barium, it is probable that the barium is actually combined as the sulfate but in so finely divided a state as to be essentially colloidal in size and hence is carried with the solution.

The occurrence of the barite as a cement in the sandstone favors the view that the barite resulted from the mingling of solutions. Water follows the more open spaces through a sand. These spaces may be within a massive or a more porous bed, along bedding planes, or along joints; hence mingling of solutions and deposition might occur any where.

It is possible that replacement of a sulfate, such as $CaSO_4$, might occur. However, $CaSO_4$ as it occurs in sandstones or siltstones is dominantly in the form of nodules or veins and not as a cement. It may be that the pure nodules (radial concretions) of barite and the veins of barite occurring to the southwest of the area under discussion originated by replacement of $CaSO_4$. This should be investigated. In the Garber formations, the barite was undoubtedly an original deposit as the crystal form of the rosette aggregates shows. The crystal form is the normal habit of the barite, which is, therefore, not a pseudomorph after any previously existing sulfate. Furthermore, no evidences of other sulfates were found within the barite, nor did any of the concretions show evidence of having replaced any previously existing mineral. The same reason applies to the sand calcites. They developed their

scalenohedronal form by initial deposition and not by replacement. It has been suggested that the barite replaced dolomite. Such a reaction is possible, but, in view of the fact that the barium is transported as the chloride and must react with a sulfate radical to form barite, introducing a replacement of dolomite or any carbonate is merely introducing a wholly unnecessary factor since the carbonate played no part in the reaction. The reaction of the chloride with the sulfate formed the $BaSO_4$ which was precipitated at once. Any open space was sufficient and no nucleus was necessary. *Subsequent* replacement might occur, but it in no way influenced the reaction. There is no more need of introducing replacement than there is of holding that all cementation of sandstones must be replacement. The barite, whether as concretions or rosettes, was a primary deposit within the interstices of the sand grains and was due to the reaction of the readily soluble $BaCl_2$ with a sulfate radical. The lighter gray color of the interior of some barite rosettes may be due to a leaching of the iron oxides on the sand grains by the chloride released in the reaction, especially if some HCl were liberated.

The rounded sandy barite concretions represent the addition of barium sulfate to all sides of an originally small barite grain. Variations in texture or in the direction from which the solutions approached would cause variations in the shape of the concretions. Probably, their rate of growth was faster than that of the crystals of the rosettes.

The crystal aggregates are typical of barite. Nodules and radiating aggregates are common features of the barite in any barite deposit. Barium sulfate crystallizes readily, and the haphazard orientation of any small crystal permits growth in any direction. A number of such crystals irregularly arranged would result in the sand barite aggregates. The dominance of a single central crystal indicates that the earlier growth was slow and chiefly along one plane. Doubtless at the initiation of such growth, other, but differently oriented grains, were deposited. That grain in which the crystallographic orientation was such as to parallel the bedding or joint plane was in a favored position to grow fastest and so outstripped its fellows. Some of the solution found its way past the edges of this fast-growing crystal so that the other grains continued to grow, but more slowly. Thus, the central crystal became large, but those on the sides also developed. Later variations in the flow

of the feeding solutions might favor the growth of the crystals on the sides. Once a crystal was well started, its orientation rather than the movements of the solutions dominated the direction of growth.

The character of the sulfate that caused deposition has not been indicated. It probably was $CaSO_4$, although not necessarily so, as magnesium sulfate, for example, might act similarly. Calcium sulfate is soluble in 536 parts of water at about 15° C., and is known to be transported by ground waters. The base exchange with $BaCl_2$ would result in a very insoluble salt and the readily soluble $CaCl_2$. Other sulfates may have played a part (the local production of H_2SO_4 from the alteration of a sulfide or the oxidation of H_2S might have been a source of the sulfate), but it seems more probable that it was the calcium salt.

The time of deposition was probably not long after the burial of the formations and before the brines they once contained had been fully removed through evaporation or displacement by fresh waters.

Summary

Barite concretions and barite crystal aggregates, known as "sand barites" or "barite rosettes," occur in sandstones in the Garber formation (and to a less extent in the underlying Wellington formation) in central Oklahoma. They are rather local in horizontal and vertical distribution. The barite in both types cements the sand grains together. The crystals of barite in the rosettes have various orientations. It is believed that the barium was derived (chiefly) from barium silicates (such as barium feldspars), barium adsorbed in colloids, or from detrital grains of barite. It was leached out by chloride waters (original brines), forming $BaCl_2$; carried a variable distance (probably short); and deposited as a cementing material in the sandstone through reaction with some soluble sulfate to form the extremely insoluble $BaSO_4$, which assumed the form of the rounded concretions or the crystal aggregates. The time of deposition was probably not long after the formation of the sandstone.

NOTES AND NEWS

GLAUBERITE CRYSTALS FROM WEST PATERSON, NEW JERSEY

A. C. HAWKINS, *Rutgers University.*

Within recent years much interest has been shown in the negative crystal cavities found in prehnite and other minerals at West Paterson. These cavities represent crystals of a number of different species, most of which are easily soluble in water, such as calcite, anhydrite, and glauberite.[1]

In 1932, Mr. John Obert discovered free glauberite crystals in the West Paterson quarry. The largest of these crystals is 2×3 cm. in size, though most of them are smaller. Their color is light gray, with a white exterior powdery coating caused by alteration, which is mostly calcium sulphate. The crystal forms shown are the base *c* and the minus unit pyramid *s* (see Fig. 1). A number of the crystals are elongated parallel to the *a* axis. Many are grouped in irregular aggregates.

With the glauberite crystals there are also small crystals of gypsum, the largest of which measures 1×2 cm. Most of them have a light brown color due to occluded dirt. The crystal forms shown are: unit prism *m*, clinopinacoid *b*, and unit minus pyramid *l*. Con-

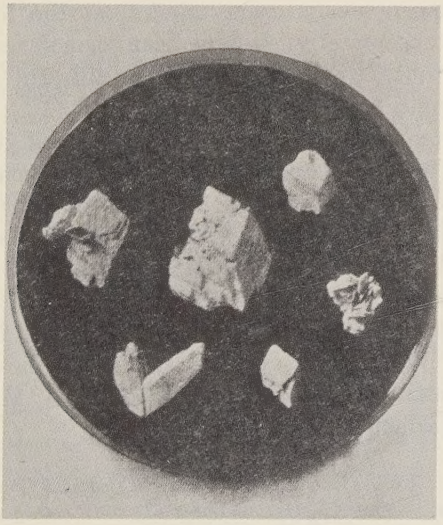


FIG. 1

tact twins on *a*, the common swallow-tail type, are present among them. A few crystals are flattened parallel to pyramid *l*, others parallel to the pinacoid *b*. Aggregates, irregularly intergrown, are numerous.

The crystals of glauberite and of gypsum occurred together and were lying loose in a cavity roughly 1×1 meter in size, which was in the solid basalt, about 2 meters below the top of the quarry wall. There was a quantity of brown dirt with the crystals in the cavity which had evidently been derived from the decomposition of the basalt.

At West Paterson there are, besides the original minerals which were developed at the time of the Triassic lava flow, a number of other minerals which have been formed, redissolved and formed again in new combinations by the circulation of underground water during the long period since the igneous activity occurred. Hence, pseudomorphs and replacements are often observed, as well as abundant negative crystal cavities which occur in a number of different minerals. If all of the mineral combinations of the West Paterson locality were fully known, it would undoubtedly be found that practically every mineral present exists in nearly every possible relation to every other mineral of the locality. Thus glauberite and gypsum crystals have been formed and redissolved a great many times, either to reappear in different mineral combinations, or simply to be formed again.

It is the writer's conviction that the crystals of glauberite and gypsum, which are here described, have been formed at some quite recent time, probably from water standing in the cavity during the glacial period (Pleistocene), when this hill of basalt was completely covered by slowly moving ice, and the level of the underground water was so high that the cavity was, for a considerable period, full of water. Since the melting of the glacial ice the cavity has become dry, but the crystals have remained to the present day.

Acknowledgment is hereby made to Mr. J. G. Manchester for the photograph which accompanies this article.

TWISTED MILLERITE CRYSTALS

A. C. Hawkins

In the anthracite coal basin at Nanticoke, Pa., the Mills coal vein is cut by narrow stringers of white quartz. In cavities which are present in this quartz, occasional aggregates of millerite crystals

are found. Some of the aggregates of millerite are radiated, while others are irregular, a mass of brilliant acicular, hair-like prisms, the longest of which measures about 2 cm.

Among the most slender of the millerite crystals there are a number which show a helical twist; they appear like ribbons which have been twisted from both ends. The twist is either right or left handed in equal numbers of the crystals.

It does not appear that the twisting can have been the result of mechanical causes, since the small twisted crystals are interspersed with thicker prisms which are not twisted. The phenomenon must have been caused by a natural tendency in the growth of the crystal. Professor Newhouse of Mass. Institute of Technology has informed the writer that millerite crystals have been found in quartz veins in a number of other coal mines, and that quite frequently they are twisted. A similar twisted condition has been noted in stibnite.

Thanks are due to Mr. T. J. Arnott of the Glen Alden Coal Company for submitting the specimens.

[1] W. T. Schaller, The Crystal Cavities of the New Jersey Zeolite Region *U.S.G.S. Bull.* **832,** 1932.

Those interested in forming a Society for Research on Meteorites, whose purpose shall be to promote the discovery, collection, investigation and preservation of meteorites, and to advance the science of meteorites and related sciences through the increase and diffusion of knowledge concerning meteorites, are asked to write to the acting secretary of the preliminary organization, Mr. H. H. Nininger, Director, The Nininger Laboratory, 1955 Fairfax St., Denver, Colorado, or to communicate with Professor Frederick C. Leonard, acting president, Dept. of Astronomy, University of California, Los Angeles, California.

Dr. Friedrich Rinne, professor emeritus of mineralogy and petrography at the University of Leipzig and honorary life fellow of the Mineralogical Society of America, died suddenly on March 12, 1933, three days prior to his seventieth birthday.

Dr. Waldemar Lindgren, Rogers professor of economic geology and head of the department of geology at the Massachusetts Institute of Technology, will retire at the end of the present academic year.

Dr. Victor Goldschmidt of Heidelberg, Germany, died on the 8th day of May in Salzburg, Austria.

At the nineteenth meeting of the Mineralogical Society of Southern California, held at the Pasadena Public Library, Dr. Ian Campbell addressed the society on the

subject "Minerals, and their Effect on Men and Nations." The tenth field trip was held at the Jensen Quarry of the Riverside Cement Co.

At the twentieth meeting, Dr. John H. Maxson gave an illustrated lecture on "The Origin and Use of Chrome-bearing Minerals." The eleventh field trip included visits to the mines at Borate, Calico and Barstow, and to the vertebrate fossil beds of the region.

At the twenty-first meeting, held on May 8, Mr. W. B. Phelps spoke on the subject "Gold, its Occurrence, Mining and Recovery."

The Rocks and Minerals Association has announced its first National Outing which will be held on July 9. It is hoped that on this day 20 field trips throughout United States and Canada will be taken under divisional directors who will conduct the outings in their respective districts. A cordial invitation is extended to fellows and members of the Mineralogical Society of America. Further information, if desired, may be obtained from Mr. Fred W. Schmeltz, 2510 Maclay Ave., New York City.

Corrections

In the article by George Tunell, "Determination of the space-lattice of a triclinic mineral by means of the Weissenberg goniometer," *American Mineralogist*, vol. **18**, pp. 181–186, 1933, on page 185, sixth line from the bottom of the page, read "that" in place of "as to satisfy the law of Bravias as stated by Friedel, according to which." Also on page 185 delete footnote 8.

In the paper by Joseph Hyde Pratt on "Gems and gem minerals of North Carolina," this statement is made in the last sentence on page 149: "This diamond is in the American Museum." It should read: "A model of this diamond is in the American Museum."